SOIL GENESIS AND LANDSCAPE EVOLUTION

IN CENTRAL OAHU, HAWAII

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ABSTRACT

The highly weathered soils of central Oahu are generally characterized as residual soils developed in basalt. These soils do not have any of the properties that are commonly associated with soils developed in volcanic ash. Most of these soils are classified as either Oxisols or Ultisols. Soils that are on the eastern footslopes of the Waianae Range are recognized as having formed in volcanic ash and are classified as Inceptisols.

Soils along a transect from the Inceptisols of the Waianae Range to the Oxisols and Ultisols of the Koolau Range were examined in this study. A discontinuity was observed in all but one profile along the transect. The stratigraphic relationships between the discontinuity and landforms strongly suggest an eolian origin for the B horizons above the discontinuity. Mineralogical analysis of the soils revealed that both the highly weathered B horizons above the discontinuity in the Oxisols and Ultisols and the B horizons in the Inceptisols which developed in volcanic ash contain very small amounts of the resistant primary minerals magnetite and ilmenite relative to soil developed in basalt. These two independent lines of evidence indicate that the highly weathered B horizons above the discontinuity in the Oxisols and Ultisols developed in volcanic ash.

The soils in central Oahu provide a record of alternating periods of landscape stability and instability. This record is the basis for constructing the following sequence of events for the landscape evolution of central Oahu: (1) erosion of Koolau and Waianae Volcanos; (2) formation of soils in residual basalt; (3) formation of alluvial

fans at the base of the Waianae Range; (4) development of soils in the Waianae alluvial fans; (5) basin-wide truncation of soil profiles and concurrent downcutting of stream channels; (6) deposition of one or more volcanic ash layers possibly separated by erosional periods; (7) formation of soils in the volcanic ash and the concurrent accumulation of tropospheric dust from mainland Asia; and (8) further downcutting of stream channels but stabilization of interfluve surfaces as evidenced by the accumulation of tropospheric dust.

The soils of the study area were also classified according to the latest version of Soil Taxonomy.

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1. INTRODUCTION

Soils have often been viewed as the end product of the influence of climate and organisms acting over a period of time on a parent material within a topographic setting (Jenny, 1941). This relationship was presented by Jenny in the form of an equation: Soil = f(climate, organisms, relief, parent material, time).

Climatic fluctuations during the Quaternary have undoubtedly influenced the composition and distribution of plant communities and soils in Hawaii. Climate changes occurred on a world-wide scale, however, the magnitude of climate change in Hawaii remains largely unknown. The paucity of information regarding former plant communities has greatly hindered paleoclimatic reconstructions in Hawaii.

The evolution of the Oahu landscape in broad terms was revealed largely through the work of Harold Stearns (Stearns and Vaksvik, 1935). He did a considerable amount of work in establishing the history of sea level fluctuations in the Hawaiian Islands. His work concerning the origin of the Wahiawa Basin (Schofield Plateau), however, did very little to elucidate the mid- to late-Quaternary history of the Basin.

In the early 1960's Ruhe (1964) did some pioneering work in modelling climate change on Oahu as a function of sea level fluctuations, and he examined the influence of paleoclimates on soil genesis (1965). He and his colleagues (Ruhe et al., 1965a, 1965b) also examined former shorelines and established the sequence of sediments in the Pearl Harbor area. Ruhe felt that there must be a reason for the apparent correlation between soils and the stepped surfaces of the Wahiawa Basin, and he hoped to coordinate a cooperative effort between the Soil Conservation Service and the University of Hawaii to study the soils, but that project was never completed.

Deciphering landscape history and pathways of soil formation where the factors and the intensity of soil forming processes have changed over time can be quite complicated. Sherman (1949; Sherman and Alexander, 1959) investigated the formation of soils on Oahu, but he apparently looked at transects along climatic gradients and never established the genetic relationships among sample sites in terms of their geology.

The purpose of this study was to gain a better understanding of the formation of the highly weathered soils of the Wahiawa Basin from a geological perspective. The objectives of this study were:

1) to demonstrate the use of stratigraphy and geomorphology to determine the parent materials of the soils of the Wahiawa Basin;

2) to propose the influence of volcanic ash and eolian deposits on the formation of soils of the Wahiawa Basin;

3) to present the tentative taxonomic classification of the soils of the Wahiawa Basin based on the latest revisions of Soil Taxonomy, and to show the relationship to soil genesis.

2. REVIEW OF LITERATURE

2.1 Geology of Oahu

According to Macdonald and Katsura (1964) and Macdonald et al. (1983), the bulk of Oahu Island, Hawaii, is composed of tholeiitic basalt and this basic rock is associated with the construction of the Waianae and Koolau Ranges (Fig. 1). The oldest Waianae lavas date to 3.8 Ma K-Ar years (McDougall, 1964), whereas the youngest are about 2.2 Ma (McDougall, 1964; Funkhouser et al., 1968; Doell and Dalrymple, 1973). The Koolau lavas date from 2.8 to 1.8 Ma (Doell and Dalrymple, 1973). The petrography and petrology of Waianae and Koolau Volcanics, respectively, were reviewed by Macdonald (1940), and by Wentworth and Winchell (1947) and Roden et al. (1984). Macdonald and Katsura (1964) wrote a general review of the chemical composition of Hawaiian lavas. A brief review of the geologic history of Oahu was presented by Stearns and Vaksvik (1935, pp. 174-179).

The Wahiawa Basin is the area between the Koolau and Waianae Ranges. Its dimensions are approximately 22 km long by 8 km wide. Elevations range from approximately 30 meters above sea level at the northern and southern boundaries of the basin to 300 meters at Schofield Barracks at the center of the basin. Kipapa, Waikakaloa, and Waikele Streams have incised deep gulches in the south side of the basin, and Kaukonahua, Poamoho, and Opaeula Streams have cut gulches in the north side.

The Wahiawa Basin formed by the coalescence of Koolau Volcano with the eroded slopes of the Waianae Range (Stearns and Vaksvik,

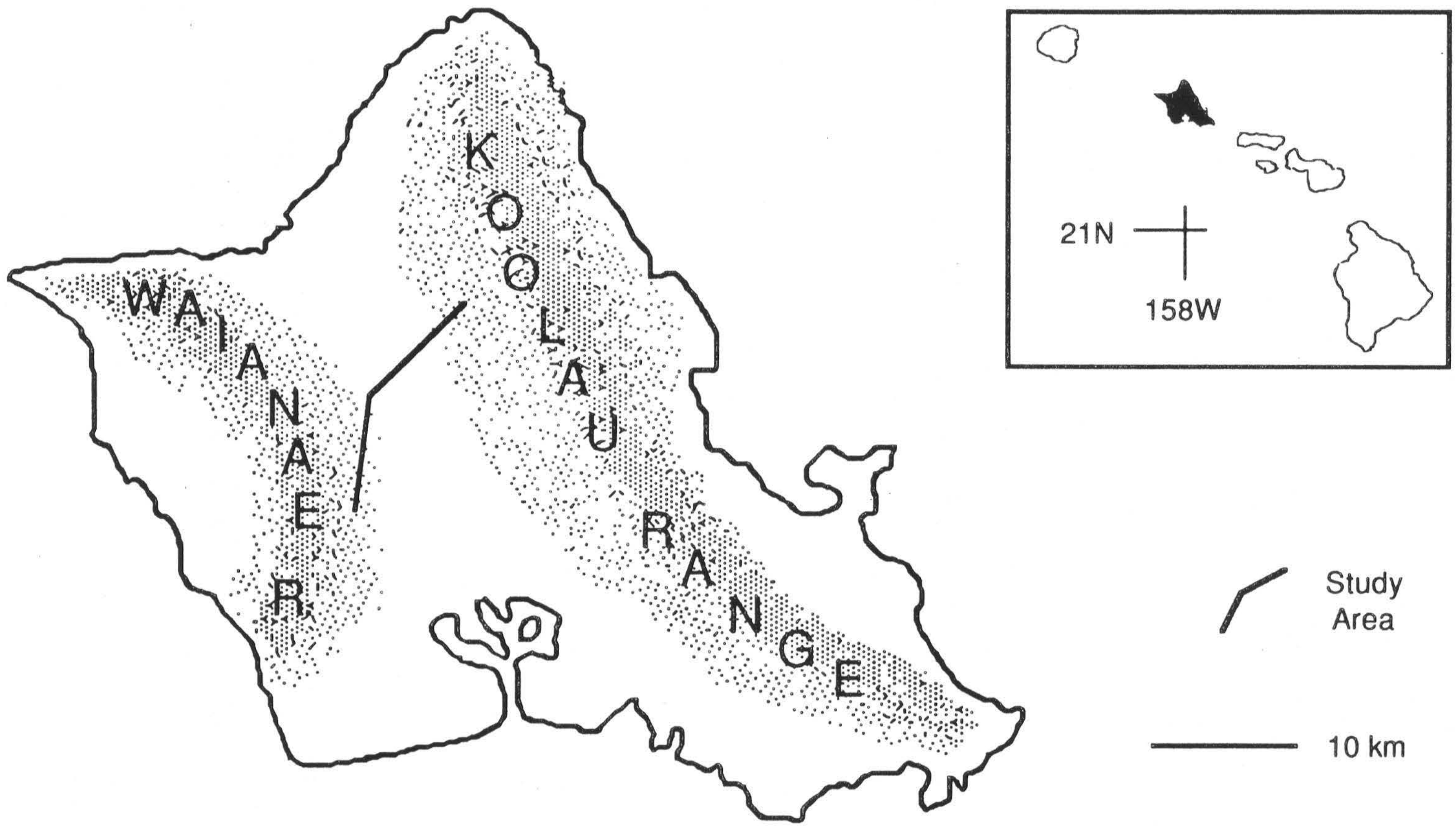

Figure 1. Map of Oahu, Hawaii, showing the study area transect. The Wahiawa Basin lies between the Koolau and Waianae Ranges.

1935). The Koolau lava beds have dips of mostly less than 3 degrees, whereas the Waianae lava beds that they overlie have dips of 10 to 20 degrees. Coalesced alluvial fans from the Waianae Range spread out over the porous Koolau basalts.

Stearns (Stearns and Vaksvik, 1935) believed that the Koolau lavas that form the basin have been only slightly modified by erosion. They believe that erosion has occurred by stripping of the lava beds layer by layer and that the amount of erosion on the interfluve divides has been small. The resultant topography is a surface with slopes more or less parallel to the original surface of the Koolau volcano.

Wentworth and Winchell (1947, p. 55) felt that the flat-topped interfluves (facets) of the leeward Koolau Range represent the original shield of Koolau Volcano. They stated that:

> The form and accordance of these facets indicate clearly enough that in a geomorphic sense they represent the original surface of the dome, an interpretation which is in no sense weakened by Stearns' insistence that parts of the facets in the Honolulu area show the stripping off of one or even several lava flows by erosion (see Stearns and Vaksvik, 1935, p. 23). Neither the loss by weathering and erosion of 25 to 50 feet from the original surface, nor the fact that the original surface displayed the flow edges and other irregularities of a lava terrane militates against the deignation of these facets as remnants of the dome surface. The view that these facets are destructional surfaces, rather than constructional, seems entirely untenable.

Based on the geomorphology and degree of stream dissection of the Koolau Range, Palmer (1955) felt that there were three main phases involved in the construction of the Koolau Range. The first phase built the southern half of the range, then a later episode built the northern half. According to Palmer's hypothesis, a third constructional phase that was centered just north of Schofield Barracks was the source of lavas that produced the smooth slopes of the Wahiawa Basin. Palmer did not present stratigraphic, chemical, or mineralogical evidence to support this hypothesis.

Wentworth and Winchell (1947) also noted the longer slope length and the lesser degree of stream dissection in the leeward northern section of the Koolau Range as compared with the leeward southern section. They considered the possibility that the northern section is younger than the southern section, but they rejected this interpretation because of lack of supporting evidence. Wentworth and Winchell (1947, p. 56) interpreted the difference between the northern and southern parts of the range to be the result of "the interference of the adjacent Waianae dome." That is, the longer slope length in the northern section is a result of "the fill of lava flows against the slope of the Waianae Range." They also pointed out that the lower elevation of the northern half of the original Koolau Volcano would have less rain and consequently less stream dissection than in the southern half of the range.

After much erosion of both the Waianae and Koolau shield volcanoes, another volcanic (post-erosional) stage ensued during mid-Pleistocene time. In southeast Oahu, lavas and pyroclastics from this time are referred to as Honolulu Volcanics (1.13 to 0.031 Ma; Gramlich et al., 1971; Lamphere and Dalrymple, 1980). The petrography and petrology of Honolulu Volcanics was reviewed by Winchell (1947) and Clague and Frey (1982).

In a reevaluation of the stratigraphy of the Waianae Range, Sinton (1986) considered the cinder cones at the south end of the range and lava flows in the Kolekole Pass area to belong to the same lithologic unit, the Kolekole Volcanics. Although the isotopic age of the Kolekole Volcanics is not known, stratigraphic relationships indicate that these deposits are post-erosional and probably Pleistocene in age (Sinton, 1986).

2.2 Climate

2.2.1 Present Hawaiian Climate

Price (1983) characterized Hawaii's climate as the interrelationship among latitude, the surrounding ocean, Hawaii's location relative to the storm tracks and the Pacific anticyclone, and the islands' terrain. A nearly uniform daylength throughout the year and the moderating influence of the ocean produces low seasonal variation in air temperature.

In addition to supplying moisture to the air, the ocean helps to maintain the moderate temperatures in Hawaii. The seasonal extremes in sea surface temperature range from about 22°C in March to a high of about 26°C in October. The extremes in average monthly means for air temperatures occur synchronously with the extremes in sea surface temperature, reflecting the overriding importance of the ocean in controlling air temperatures.

During the summer months, the Pacific anticyclone dominates and produces the persistent northeasterly trade winds. As these winds rise in response to the topography, they cool and the moisture they carry precipitates. As a result, rainfall increases rapidly from the coastlines to the mountain tops (Leopold, 1951). On the low islands (below 1500-meter elevation) the maximum rainfall occurs immediately to the lee of the mountain crests. The temperature inversion, which characterizes the trade wind periods, limits the highest convective clouds to about 2100 m. Mountains between 1500- and 2100-meter elevation receive maximum rainfall at their summits. The mountains that rise above the inversion receive their maximum precipitation at an elevation of 900 to 1300 meters, while the mountain tops are arid.

Similar rainfall patterns occur in the winter but cyclonic storm rainfall occurs when the southerly portions of frontal systems pass over Hawaii (Leopold, 1951). Yeh, Carson, and Marciano (1951) found a marked correlation between the jetstream and winter precipitation. Analyses by Yeh, Wallen, and Carson (1951) revealed that under the current circulation patterns, winter precipitation is due as much to the increase and intensity of trade wind rain as it is to the increased frequency of cyclonic rain.

In summary, the present Hawaii climate is characterized by an orographic-convective cell which produces localized, intensive rainfall centers from trade winds near mountain summits which serve as focal points for rainfall activity regardless of wind direction (Ruhe, 1964).

The characterization of Hawaii climate in the Koppen and Thornthwaite systems can be found in Jones and Bellaire (1937). Isohyetal rainfall maps of Oahu have been compiled by Giambelluca et al. (1986).

2.2.2 Geologic Evidence of Paleoclimates

Stearns and Vaksvik (1935) hypothesized that before the summit of the Koolau Range was lowered by erosion, the northwest part of the range was more sheltered from trade wind rains than now. The relatively youthful stream development stage, furthermore, was interpreted to be relict from a time when the trade winds were more easterly than at present. Stearns and Vaksvik (1935) estimated the summit of the Koolau Range to have been about 1500 meters high prior to its reduction by erosion, and it may have received double its present rainfall. It was at this time that the great valleys of the Koolau Range were incised.

Numerous papers have documented the occurrence of emerged and submerged reef deposits in the Hawaiian Islands (Stearns and Vaksvik, 1935; Stearns, 1935, 1974, 1978; Ruhe, 1964, 1965; Ruhe et al., 1965a; Macdonald et al., 1983). Stearns (1978) summarized the various recognized relict shorelines in the Hawaiian Islands. The shorelines range in elevation from about -1,100 to +365 meters. The authenticity of some of the shorelines is open to debate (Macdonald et al., 1983), and it is obvious that glacio-eustatic changes alone cannot account for the range of elevations. Sea level could be lowered by about 130 meters during a glacial maximum and could be raised about 65 meters if all existing glacial ice melted (Donn et al., 1962; Flint, 1971). Moore and Moore (1984) attributed the +365 meter shoreline to a very large tsunami.

In Hawaii, stream terraces are correlated with high stands of sea level (Macdonald et al., 1983). Ruhe (1961, 1965) and Ruhe et al. (1965b) related changes in stream gradients to changes in macroclimate.

Sea level fluctuations around Hawaii have resulted in the relative raising or lowering of the existing topography relative to the orographic-convection cells produced by the trade winds (Ruhe, 1964, 1975). Ruhe analyzed the meteorological statistics that characterize the present climate on Oahu and derived equations that quantitatively describe the amount of precipitation that could be expected with respect to elevation and distance from the summit on the leeward side of the Koolau Range. His calculations showed that a lowering of sea level by 100 meters could have produced as much as 100 percent increase in rainfall in parts of the Wahiawa Basin. Conversely, a rise in sea level by 30 meters may have caused a decrease in rainfall by as much as 50 percent.

The main assumption underlying Ruhe's paleoclimate estimates was that the general circulation pattern during both glacial and interglacial periods basically resembled that of today; that is, precipitation related to trade winds was responsible for most of the rainfall. The extent to which Hawaii climate actually differed between glacial and interglacial periods is not known.

Molina-Cruz (1977) has interpreted abundances of pelagic quartz, opal, and radiolarian assemblages as indicating increased trade wind velocity in the equatorial Pacific during glacial periods. Chuey et al. (1987) reported that the grain size of pelagic eolian sediment indicated "a general correlation between glacial maxima and increased wind velocity, but atmospheric circulation intensity commonly fluctuates at a higher frequency than the glacial cycles." Both Chuey et al. (1987) and Janecek and Rea (1985) cited evidence of greater variability in wind velocity prior to 300,000 years ago than in the later record.

2.2.3 Fossil Plant Evidence

The Salt Lake Tuff was deposited during a low stand of the sea, probably during the Waipio stand of the Illinoian glacial period (Macdonald et al., 1983). The tuff contains many fossil plants found in an upright position, which indicates that they were not transported there by stream action (Selling, 1948; Hay and Iijima, 1968). A total of fifteen species including koa, ohia, and loulo palm have been identified. These trees were collected from an area that now receives 500 mm of rain annually. If the ecological amplitudes of these plants has not changed significantly, rainfall in the Pearl Harbor area at the time of tuff deposition could have been 1,000 to 1,750 mm annually.

Selling (1948) wrote the only published palynological study in Hawaii. He examined the pollen found in the mountain mires of Kauai, Molokai, and Maui. The bogs and swamps that contain the pollen range in elevation from 1200 to 1765 meters and currently receive high precipitation (5000 mm). Selling (1948) recognized three major pollen zones. Zone I pollen accumulated during the last glacial period and is characterized by a dominance of xerophytic subalpine species, with rain forest vegetation being more restricted than at present. Selling interpreted this distribution of plants as indicating the depression of the inversion layer. This interpretation basically agrees with Porter's (1979) estimate of treeline depression on Mauna Kea to an altitude of 2000 meters during that time.

Selling's Zone II pollen reflects the dominance of rain forest vegetation. Zone II pollen was interpreted as representing the period of maximum post-glacial warmth (the Hypsithermal) when rain forest vegetation probably extended several hundred meters higher than today.

Zone III represents the change in vegetation to its present composition. Rain forest vegetation is not well represented, but it does not seem to indicate that conditions were as dry as those that prevailed during Zone I pollen. Selling's interpretation was that the inversion layer was lower than it was during Zone II, and the vegetation displacement may possibly represent increased cyclonic activity.

2.3 Pedology and Climate Change

Most soil scientists in Hawaii apparently have not taken climatic fluctuations into account in their interpretations of soil formation (e.g., Hough and Gile, 1941; Sherman et al., 1948; Sherman, 1949; Sherman and Alexander, 1959; Tanada, 1951; Tamura et al., 1953). Sherman (1949) and Sherman and Alexander (1959) made interpretations concerning the genesis of Oxisols based specifically on present climatic conditions. Cline (1955) correlated soil genesis and distribution with present climatic zones. Failure to distinguish current soil forming processes from those processes that have ceased to operate can lead to spurious conclusion concerning the rate of soil genesis and the combinations of processes responsible for profile differentiation.

As pointed out by Ruhe (1964, 1965), climatic fluctuations have affected soil genesis and distribution in Hawaii. Formation of parent materials, changes in topography, duration of exposure to subaerial weathering, and vegetation distribution have all been correlated with climate fluctuations in Hawaii.

Deciphering the effects of climatic change on the soils of the Wahiawa Basin is complicated because these soils have probably experienced several climatic oscillations. There is the additional problem of "pedogenic inertia" (Bryan and Teakle, 1946) or "pedogenic persistence" (Finkl, 1980). That is, once clay mineralogy has reached an advanced degree of weathering (i.e., kaolinite, sesquioxides) it becomes increasingly difficult for subsequent climates to leave indelible imprints upon the soil (Nikiforoff, 1953; Bryan and Albritton, 1943).

The situation is further complicated by the superposition of soil profiles (Birkeland, 1974) as indicated by lithologic discontinuities. Hunt (1972) considers profile superposition to be the rule rather than the exception for unglaciated areas. Modenesi (1983) has noted that inverse or disordered weathering sequences within soil profiles indicate the superposition of parent materials.

2.4 Geomorphology

A geomorphic surface can be defined as a "mappable part of the land surface that is defined in terms of morphology, origin, age, and stability of component landforms" (Soil Conservation Service (SCS), 1984). A geomorphic surface implies an episode of landscape development. Ruhe et al. (1965b) described four geomorphic surfaces on the Ewa Coastal Plain. These surfaces are below 30-meter elevation and are attributed to erosion and sedimentation caused by fluctuating sea levels in response to glacial-interglacial cycles.

As mapped by Ruhe (1975), there are eight stepped geomorphic surfaces in the southern Wahiawa Basin on interfluves that extend from the Ewa Coastal Plain up the slopes of the Koolau Range. Each surface is bounded by scarps that separate it from higher and lower surfaces. The elevations of these surfaces range from 30 meters up to approximately 400 meters. On the Waianae side of the basin there are six surfaces on the interfluves extending up to about 400 meters. The two highest surfaces mapped on the slopes of the Koolau Range are not present on the Waianae Range. Because Ruhe neither defined his mapping units nor described his mapping methods, the basis for his delineations is unknown.

In a constructional landscape model, the distal ends of lava flows would form the scarps separating geomorphic surfaces, and there would have been only slight modification of the landscape by erosion. The boundaries of geomorphic surfaces would be placed at the foot of the scarps. Consequences of the constructional landscape model are that the geomorphic surfaces become progressively younger upslope, and the soils developed on these surfaces are primarily residual.

Wentworth and Winchell (1947, p. 59) reported that scarps are common on Koolau Volcano surfaces:

> From variations in the attitude of Koolau lavas it is evident that they flowed over a surface on which abrupt irregularities of 5-10 feet were common. Such a surface would be produced by lava flow units averaging about 10 feet thick. Locally, excesses of slope may be found which show dips of 15 or 20 (degrees) for distances up to 100 feet. Structures indicating the cascading of a lava flow over a cliff 10 or 20 feet high are occasionally found. All these irregularities are subordinate to the wavy configuration due to slight variations in thickness of the flow units.

The stepped surfaces of the Wahiawa Basin form an arcuate pattern that more or less follow the contours around the southern half of the basin, and cut across several parent materials (Ruhe, 1975). The surfaces appear to extend across Koolau basalts, Waianae basalts, and old alluvium from the Waianae Range, which indicates that they are erosion surfaces which are not simply controlled by erosion-resistant strata.

Marine erosion by a former high stand of the sea is a process that could account for the arcuate pattern of the geomorphic surfaces. However, eustatic sea level fluctuations can only account for these stepped surfaces up to an elevation of about 65 meters, which is the theoretical maximum high stand of the sea if all glacial ice were to melt (Flint, 1971). Furthermore, the evidence for former high stands of the sea on Oahu above 30 meters is inconclusive (Macdonald et al., 1983).

Ruhe (1960) objected to the hypothesis that the geomorphic surfaces of the basin were created primarily by constructional processes:

> Cursory examination of the stepped sequence of surfaces does not preclude the possibility that some of the scarps may be structurally controlled. They may be held up b more resistant lava flows. As a result a pseudo-multicyclic erosional landscape actually may be unicyclic with definite structural control of scarps.
>
> Local opinion implied that the stepped sequence of scarps may be only slightly modified distal edges of lava flows. This would require progressive overlapping of successively younger flows, i.e., that each succeeding flow did not extend as far from the source as its predecessor.
>
> This requires, too, that only weathering has modified flow surfaces to form soils. Erosion has been insignificant. Further required is that only one cycle of erosion, the last gulch cycle, has been active on the island. Yet there are integrated drainage patterns on the various levels of the stepped sequence, ... classic evidence of multicyclic erosion.
>
> The stepped sequence of surfaces probably is a multicyclic pedimented-type landscape. Such multicyclic landscape requires intermittent tectonic disturbance of the island of Oahu, eustatic changes in sea level of the Pleistocene, or a combination of both.

In addition to the stepped sequence of surfaces on Oahu, Ruhe (1961) recognized similar landforms on Kauai, Maui, Molokai, and Lanai.

Whether the arcuate pattern of geomorphic surfaces around the southern half of the Wahiawa Basin was due either partially or wholly to erosion has not been investigated. Consequences of an erosional model of geomorphic surface formation are that the surfaces become progressively older upslope (Daniels et al., 1971; Ruhe, 1969; Hall, 1983), and soils formed on these surfaces may have formed primarily in transported sediments.

Ruhe et al. (1965a) dated the stepped surfaces of the Wahiawa Basin as pre-Kaena shoreline, i.e., older than 500,000 years BP (Stearns, 1978). The reasoning behind this was that a cliff formed by marine erosion dating to this stand of the sea cut into the lowest (and therefore youngest) surface of the basin. This surface, therefore, must have existed prior to Kaena time.

Another attempt to deduce the age of the surfaces was made by Jackson et al. (1971). They examined Wahiawa Basin soils with high quartz and mica contents. Because basalt does not contain either quartz or mica, the occurrence of these deposits at high elevations on Oahu is anomalous. Quartz is only known to have formed on Oahu at volcanic vents where it is the product of hydrothermal alteration. The investigations by Rex et al. (1969) and Clayton et al. (1972) indicated that the quartz-rich deposits on Oahu were eolian materials that probably originated in Asia. Dymond et al. (1974) reported a K-Ar age of 170-203 Ma for the mica in the eolian deposits, an indication that the mica did not form *in situ*. Moreover, low soil solution potassium indicated unfavorable thermodynamic conditions for mica formation under present conditions (Swindale and Uehara, 1966).

Based on a sedimentation rate of 1 meter per 10^6 years for these eolian materials in deep sea sediments (Goldberg and Koide, 1962; Windom, 1969), Jackson et al. (1971) calculated that it would require 200,000 to 500,000 years for the quartz-rich deposits to have accumulated on the high elevation surfaces of the Wahiawa Basin.

This estimate may be inaccurate for several reasons. Tropospheric dust accumulation in pelagic sediments in the North Pacific fluctuated at periodicities similar to those of glacial-interglacial cycles (Janecek and Rea, 1985), with higher accumulation rates associated with arid glacial periods (Chuey et al., 1987). Chuey et al. also reported greater eolian input in pelagic sediments between 800,000 to 300,000 ka, and that sedimentation rates have varied from 0.5 meter to 3 meters per 10^6 years.

The accumulation of these eolian deposits was evidence of the relative stability of the higher surfaces of the Wahiawa Basin. Jackson et al. (1971), however, noted that there were no landscapes on Oahu that have accumulated the estimated 2 meters of tropospheric dust that should have been deposited since quiescence of Koolau Volcano. They offer the following interpretation regarding the high elevation surfaces on which the Paaloa soil has developed:

> The indication is, therefore, that the soils are on secondary, though old, landscape surfaces. In this connection, Paaloa landscapes appear to lie nearly parallel to the original basalt dome surface. The Paaloa areas may represent denuded and weathered lava flow surfaces which had lain parallel with the original dome surface. The gravel lines in the parent material observed (R. H.(sic) Ruhe, personal communication) under some Paaloa profiles also indicate secondary reworking in some areas.

Soils on low elevation surfaces of the Wahiawa Basin have smaller amounts of quartz than do high elevation surfaces (Jackson et al., 1971). This could be explained in part by low rainfall at low elevations, and, assuming that most rainfall is associated with tradewinds, that most of the tropospheric dust was scrubbed from the atmosphere before it reached the lower elevations. Jackson et al. felt that rainfall alone could not account for the low quartz content on these surfaces because rainfall along the transect did not change as abruptly as did the quartz content in the soils.

Jackson et al. (1971) suggested that there must have been considerable sheet erosion on the lower surfaces to reduce the quartz content. If this were true, these low elevation surfaces, which have 0-3 percent slopes and receive low rainfall, would therefore be younger and less stable than the high surfaces which are steeper (3-12 percent slopes) and receive more rainfall. This interpretation may be feasible if areas mapped as Paaloa soils (greater dust accumulation) did not experience semi-arid conditions, which are prone to erosion (Chorley et al., 1984), for any significant duration since the onset of dust accumulation. However, neither paleoclimatic changes, shifts in the ranges of vegetation communities nor agricultural mixing of topsoils were apparently taken into consideration by Jackson et al. in their analysis of topsoil quartz content.

2.5 Soils

2.5.1 Soils with Oxic Properties

Oxisol distribution tends to be independent of present climatic conditions (Buol et al., 1980). This suggests to Buol et al. (1980, p. 302) that many Oxisols have formed in transported, pre-weathered materials. Former climates more conducive to Oxisol formation may have also influenced their genesis (Soil Survey Staff, 1975; Moorman and Van Wambeke, 1978). Relatively stable upland summits that may be relict erosion surfaces, alluvial terraces, or pediments, are positions where Oxisols are commonly found (Buol, 1979).

Eswaran and Tavernier (1980) cite several attributes of a "typical" Oxisol developed on basalt under an isohyperthermic soil temperature regime and a udic soil moisture regime. There is little or no clay translocation, very little textural change with depth, and a fairly uniform mineralogical and chemical composition with depth. These characteristics indicate a rapid and uniform movement of the weathering front, and the weathering processes did not produce significant clay translocation. They conclude that intense weathering, more so than pedogenic processes, is responsible for Oxisol formation. The influence of organic acids (i.e., pedogenic processes) on the formation of oxic horizons has been reviewed by Van Wambeke et al. (1983, p. 343).

Desilication and hydrolysis, along with the concommitant accumulation of sesquioxides, are the dominant mechanisms producing oxic materials (Buol et al., 1980; Herbillion, 1980). Iron oxides precipitated on clay surfaces bind clays into microaggregates and inhibit clay translocation. The formation of an argillic horizon is also inhibited. Even so, it is difficult to imagine that the genetic processes responsible for the formation of low activity clays Ultisols are any different from those responsible for the formation of Oxisols (Isbell, 1980). Pedogenic theory does not adequately account for the fact that soils with oxic horizons and those with argillic horizons of similar clay activity merge in the soilscape in many areas of the world (Buol, 1986).

Ultisols are characterized by the following pedogenic processes: intense weathering and leaching of bases, formation and translocation of clays, and the accumulation of sesquioxides (Miller, 1983). With the exception of sufficient clay translocation to form an argillic horizon, Ultisols are similar to the concept of Oxisols. The current version of Soil Taxonomy (Soil Survey Staff, 1987), however, allows for Oxisols with kandic horizons (i.e., horizons with an increase in clay with depth just as in Ultisols, but the clay need not be illuvial, and it must have oxic chemical properties). The influence of this revision in Taxonomy on the classification of the soils in the study area is examined later.

Eswaran (1981), Eswaran and Sys (1979), and Miller (1983) have outlined the conditions necessary for argillic horizon formation. Conditions in soil surface horizons need to be conducive to dispersion, dispersed clay needs to be translocated, and translocated clay needs to be deposited in some subhorizon in the form of clay skins. Isbell (1980) pointed out that the genesis of argillic horizons is still problematical because the dominant processes involved, the necessary time span needed, and the optimal environmental conditions required for argillic horizon formation have yet to be satisfactorily identified.

Lepsch et al. (1977) found that relief was the only soil forming factor consistently identified with argillic horizons in the Occidental Basin of Brazil. Argillic horizons occurred on backslopes to footslopes adjacent to Oxisols. They postulated that argillic horizon formation may be related to the reduction and subsequent movement of hydrated iron oxides due to lateral water movement in the surface horizon. There was less free Fe_2O_3 in horizons above the argillic horizon, but the Fe_2O_3 to clay ratio was higher than in the argillic horizon. Lepsch et al. interpreted the higher ratios as the result of removal of deferrated clay. Once iron was depleted in a horizon, clay could be released from previously iron-cemented aggregates and then translocated to form an argillic horizon.

Extractable Fe and Fe_2O_3 data (USDA, 1976) of soils in the Wahiawa Basin did not conclusively support the soil genesis model proposed by Lepsch et al. (1977b). Data for several Paaloa Series profiles (which have eolian surface horizons unrelated to the subsoil), had extractable Fe_2O_3 contents in surface horizons that were both lower and higher than that of the subsoil.

Data (USDA, 1976) from two profiles of the Manana Series showed conflicting trends with respect to extractable Fe_2O_3. One profile had a lower Fe_2O_3 content in the surface horizon relative to the subsoil. The other profile had almost twice as much Fe_2O_3 in the surface horizons as in the subsoil. However, although it was not indicated in the soil profile descriptions (USDA, 1976; Foote et al., 1972), the Manana Series is characterized by a lithologic discontinuity. The description of the representative Manana profile (Foote et al., 1972) states that a "nonporous, panlike sheet, 1/8 inch to 1/4 inch thick" caps the Bt horizon. Cementation of clay by iron oxides along with a nonporous cap at the top of the Bt horizon would probably preclude clay translocation. The most reasonable interpretation of the Manana profile was that it consisted of a truncated paleo-argillic horizon overlain by pedisediment and/or volcanic ash.

In Brazil, Moniz and Buol (1982) reported an Oxisol-Ultisol-Alfisol toposequence in unconsolidated deposits containing virtually no weatherable minerals. They hypothesized that as a slope develops, the granular structure of the oxic horizon was transformed into a subangular blocky or compressed layer by alternating saturation and desiccation. An argillic-like morphology and greater bulk density were the result of this process. They did not mention illuviated clay being associated with this process.

Beinroth et al. (1974) reported Oxisols on gentle slopes and Ultisols on steeper slopes on Kauai. They hypothesized that the shearing action of soil moving downslope on the steep slopes may loosen some clay which would then be available for translocation.

Isbell (1980) has noted that although clay illuviation was the process by which argillic horizons were supposedly formed, there were four ways by which textural contrasts in soils could originate: (1) sedimentary layering resulting from an initially non-uniform parent material, (2) downward translocation of clay within an initially homogeneous material, (3) formation of clay *in situ* by differential weathering, (4) authigenesis of clay through precipitation of clay mineral constituents. All of these situations may occur within a soil, and it can be extremely difficult to identify the process(es) responsible for the textural contrast. Proper interpretation of the data depends on establishing the uniformity of the soil system

(Arnold, 1979). Arnold (1968) also showed that a variety of interpretations of soils data were possible depending on the assumptions made concerning the presence or absence of lithologic discontinuities.

Soil Taxonomy (Soil Survey Staff, 1987) waives the requirement for a clay increase with depth if there is a litholgic discontinuity in the profile. To have an argillic horizon in a truncated soil, there must only be evidence of clay illuviation below the discontinuity.

2.5.2 Classification and Distribution of Wahiawa Basin Soils

Most of the soils in the Wahiawa Basin were mapped as Oxisols and Ultisols (Foote et al., 1972). A transect ascending from the Pearl Harbor area to the flanks of the Koolau Range passes through the following sequence: Torrox - Haplustox - Eutrustox - Tropohumults. On the Waianae side of the basin, where volcanic ash occurs, soils pass through the following sequence ascending from the Pearl Harbor area: Torrox - Haplustox - Eutrustox - Humitropepts - Dystrandepts. Haplustox are mapped on the steep slopes along gulches, which contradicts the generalization that Oxisols occur on gentle slopes.

Dudal and Soepraptohardjo (1960) reported Latosols (Oxisols) developed in volcanic ash in Indonesia; they thought that Low Humic Latosols (Oxisols; e.g., Wahiawa Series) of Hawaii had passed through the same "general trend of evolution" as the red Latosols of Java (i.e., both formed in volcanic ash). Macnish et al. (1987) also reported Oxisols developed in volcanic ash in Australia.

The upper part of the solum of the Kolekole and Mahana series has developed in volcanic ash. At low elevations in the southern and eastern slopes of the Waianae Range, both of these series occur adjacent to Oxisols and there are delineations of both series which are surrounded by Oxisols. This distribution suggests that at least some Oxisols may have developed in volcanic ash. In addition, the Mahana series has both oxic and andic properties. The Mahana series has been classified both as Oxic Dystrandepts (Foote et al., 1972) and as Typic Acrohumox (USDA, 1976).

In some areas of the Wahiawa Basin, different kinds of soils have been mapped (Foote et al., 1972) on adjacent interfluves at similar elevations and distances from the Koolau summit (and therefore, presumably, similar parent materials and climate). An example of this is shown on sheet 50 of the soil survey (Foote et al., 1972) where Leilehua Series (Humoxic Tropohumults), Manana Series (Orthoxic Tropohumults), and Wahiawa Series (Tropeptic Eutrustox) occur on adjacent interfluves and are all mapped adjacent to and topographically lower than the Paaloa Series (Humoxic Tropohumults). The cause of this distribution of soils is not known.

Foote et al. (1972) mapped alternating delineations of Oxisols and Ultisols extending up some interfluves. Although these Ultisols are now classified as Oxisols according to the most recent version of Soil Taxonomy (Soil Survey Staff, 1987), the distribution of these soils may shed light on their formation. Both soil orders were mapped on the same geomorphic surface in some areas. On any one surface the soil parent material should have experienced the same set of soil forming factors, and the same kind of soil would therefore be expected to have formed. It is, therefore, hard to envision how pedogenic processes produced these alternating delineations of Oxisols and Ultisols.

De Villiers (1965) showed that the distribution of Inceptisols and Oxisols in Natal, South Africa, was influenced by erosion. Inceptisols formed in pedisediment where erosion completely removed underlying oxic material. Oxisols were found adjacent to the Inceptisols, but only where removal of the oxic material was incomplete. The result was a sequence of pairs of Oxisol-Inceptisol delineations separated by microscarps. Similar relationships existed for Mollisols and Ultisols, where Ultisols occurred where there was incomplete removal of an argillic horizon.

The erosion-sedimentation model proposed by De Villiers (1965) may explain the alternating Oxisol-Ultisol sequences found in the Wahiawa Basin. Ultisols may have been mapped where thin pedisediment and/or volcanic ash overlaid a partially eroded argillic horizon. Oxisols may have been mapped where thick, pedisediment and/or volcanic ash overlaid a truncated argillic horizon or saprolite. Oxisols could also have been mapped where relatively thin pedisediment overlaid saprolite without signs of either clay illuviation or a discontinuity.

3. METHODS OF ANALYSIS

3.1 Field Studies

Several interfluves south of Wahiawa were originally selected for this study, but the study area was changed to north of Wahiawa to take advantage of trenches excavated for a drip irrigation system. Volcanic ash derived soils in the Kunia area were included in the study after field investigations in the Poamoho area indicated the possibility of volcanic ash parent material.

Soils at twenty sites formed the transect examined in this study. These sites extended from just south of Kunia Camp to the high elevation slopes of the Koolau Range northeast of Poamoho Camp (Figs. 2 and 3). In the Kunia-Schofield area, topographic coverage is on the Schofield Barracks Quadrangle (USGS, 1953b). Aerial photo coverage is available at 1:24,000 and 1:48,000 scales. The former is on EKM-1CC-95, 96, 97 (USDA, 1962); the latter is on GS-VEEE 9-23, 24 (USGS, 1977). In the Poamoho area, topographic coverage is provided by Haleiwa and Hauula Quadrangles (USGS, 1960 and 1953a, respectively). Aerial photo coverage is available at 1:24,000 and 1:48,000 scales. The former is on EKM-1CC-98, 99, 118, 119, 141, 142 (USDA, 1962); the latter is on GS-VEEE 6-45, 46 and 9-24, 25 (USGS, 1977).

Soils distribution along the transect is shown in Figures 2 and 3. The soils in the Kunia area are mapped as Inceptisols and Oxisols (Foote et al., 1972, sheets 41 and 42). The general sequence of Kolekole-Kunia-Wahiawa series occurred from high to low elevation. In general, the soils in the Schofield-Poamoho area are mapped as

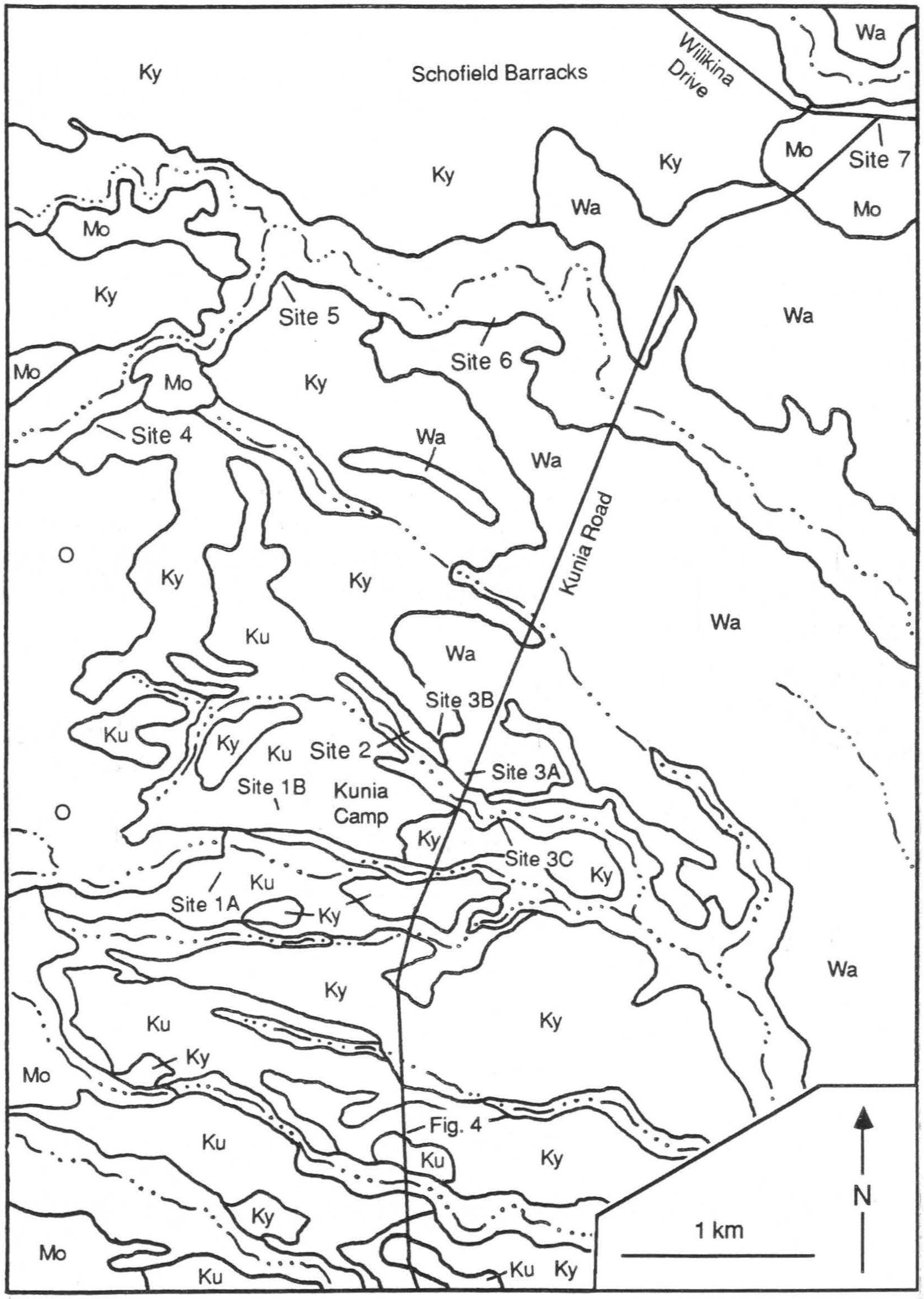

Figure 2. Locations of sampling sites in the Kunia-Schofield area and the soils shown in Fig. 4. Soils base map simplified after Foote et al. (1972). Key: Ku = Kolekole series; Ky = Kunia series; Mo = Manana series; Wa = Wahiawa series; O = other map units.

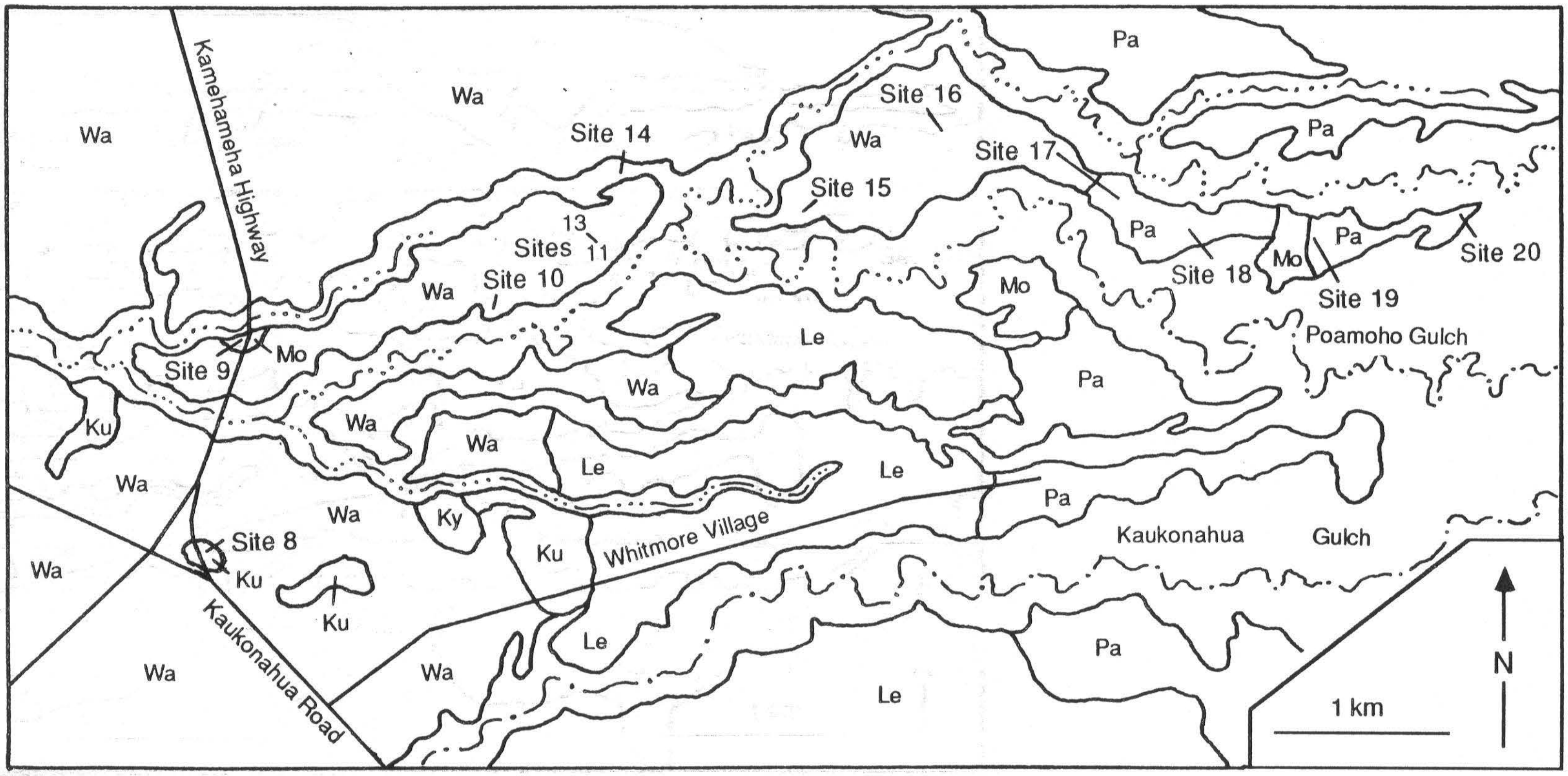

Figure 3. Locations of sampling sites in the Poamoho area. Soils base map simplified after Foote et al. (1972). Key: Ku = Kolekole series; Ky = Kunia series; Le = Leilehua series; Mo = Manana series; Pa = Paaloa series; Wa = Wahiawa series.

Oxisols at low elevations and Ultisols at high elevations (Foote et al., 1972, sheets 40, 41 and 50).

The soils at all sites were sampled according to the genetic soil horizons recognized in the field. The samples were either collected from trench walls (Sites 1, and 11 through 14), freshly dug pits (Sites 15 through 18), or existing pits (Site 20), soil exposed in gulch walls (Sites 2 through 4), or roadcuts (Sites 5 through 9, and 19). The outermost 15 cm or so of exposed soil was discarded before sampling.

Samples from the different sites were collected at various times: Site 1 in January, 1987; Sites 2 and 3 in March and April, 1988; Sites 4 through 8 in May, 1988; Sites 9 through 20 in July and August, 1986.

3.2 Laboratory Procedures

Samples were collected in plastic bags in the field and air dried in the laboratory. All analyses except bulk density were done on the fine-earth fraction of the soil, i.e., less than 2 mm in diameter.

3.2.1 Mineralogical Analysis

X-ray diffraction was used to identify the minerals present in the soils. The instrument used was a computer controlled Philips diffractometer with a vertical goniometer equipped with a theta-compensating divergence slit and a curved graphite monochrometer in place of a K-beta filter. The samples were step scanned with an integration interval of two seconds per 0.05 degree 2-theta step. A 0.2 mm receiving slit was used in the diffracted beam for all samples.

Air-dried, whole soil samples that passed a 325-mesh sieve were analyzed (Jones et al., 1982). Prior to sieving, the samples were crushed by hand so as to avoid contamination from clasts of extraneous material. This procedure was necessary in the horizons above the discontinuity which had clasts of material from below the discontinuity. In the soils of the Kunia area, these clasts were especially noticeable by their brownish color and their greater density which made them more resistant to crushing. Clasts were less noticeable in the soils of the Poamoho area, and the potential for contamination (especially magnetite and ilmenite) was therefore greater.

In an effort to produce randomly oriented samples, bulk powder mounts were used for x-ray diffraction analysis. The resulting phyllosilicate intensities were, therefore, considerably reduced as compared to oriented glass slide mounts. In general, quartz intensities were also low when bulk powder mounts were used as opposed to glass slides, apparently as a result of dilution.

The clay fraction of many samples was X-rayed, but the information from these diffractograms is not included in this document. Although the phyllosilicate minerals produced stronger intensities on oriented glass slides, this method had drawbacks. Either because of their high densities or large particle size, ilmenite and magnetite were not found in the clay fraction. As shown later, these primary minerals are important for interpretations concerning the origin of parent materials.

Typically glass slides strongly scatter x-rays in the angular range of 20° to above 60° 2-theta, the same range where x-ray amorphous (short-range order materials produce strong background intensities. Therefore, in order to assess background scatter in terms of amorphous materials, commonly present in volcanic ash, only bulk powder mounts were used.

In all x-ray diffractograms, the area under peaks of different minerals are assumed to be positively correlated with the quantities of minerals. Therefore, the areas under peaks are used as a basis for comparison of mineral quantities among soil horizons.

The differences in amounts of resistant minerals was quantified by a curve fitting, peak decomposition computer program (Jones, 1989). Horizons representing three parent materials were analyzed from three profiles. The pseudo-Voigt function (product of the intensity, full width at one-half maximum, and Voigt shape functions) was used to compute the areas under the 220 (2.96 A) magnetite peak and the 104 (2.74 A) ilmenite peak. These areas were used as a basis of comparison among horizons. In the tropospheric dust samples, the 220 maghemite peak was added to the 220 magnetite peak because it was assumed to be a weathering product of the magnetite.

The x-ray diffractograms of selected samples from each site are presented in Appendix E. The diffractograms of these same samples is also presented on microfiche in Appendix H.

3.2.2 Physical Analyses

Bulk density was determined by the clod method (Blake, 1965) using wax. The bulk density values were expressed on an oven-dry basis and were the averages of a minimum of two samples from each horizon.

Particle size distribution was estimated by several methods: pipette (Kilmer and Alexander, 1949), centrifuge (Jackson, 1956), and 1.5 MPa water content (Richards, 1965). Agreement among these methods was poor. A problem common to the pipette and centrifuge methods was the significant difference in particle densities of the soil constituents (e.g., hematite vs. kaolinite). A more serious problem was the difficulty of dispersing sand-sized aggregates of clay. Some of the "sand" from the pipette method was composed of clay aggregates; the extent to which the silt fraction was poorly dispersed was not known. Presumably, some of the "silt" were also clay aggregates.

Raising the suspension to pH 7, then shaking vigorously seemed to break up the aggregates sufficiently so that the sand fraction was composed of primary particles. This treatment, however, caused some samples to form very thick suspensions that passed through a 325 mesh sieve with difficulty. When centrifuged, much (up to 65%) of these suspensions settled out in the silt fraction although they were probably mainly clay. It was not known to what extent this problem contributed to the silt fraction in soils that easily passed through the 325-mesh sieve.

Given the above problems it was felt that 1.5 MPa water content multipied by 3 (Soil Survey Staff, 1987) would provide an adequate estimate of clay content. Errors also occurred with this method. It was unlikely that any of the soils that were estimated to have 100% clay did not have any sand fraction, especially those soils with large magnetite and ilmenite contents.

The clay estimation method described above was used for all samples except the Bw horizons of Site 2, which were composed of volcanic ash. Estimates of clay content in volcanic ash derived soils using this method gave unrealistically high values. Values based on 1 kg of whole soil were reported for these horizons for analyses where results are usually reported on 1 kg of clay basis (e.g., CEC).

Neither sand nor silt content was needed to classify the soils. Sand content has been used as a criterion for recognizing discontinuities within profiles (Oertel and Giles, 1966; Wang and Arnold, 1973). Given the small amounts of sand in the soils of the Wahiawa Basin, however, sand content is probably not a reliable indicator of discontinuities.

3.2.3 Chemical Analyses

Organic carbon was determined by dry combustion using a LECO Carbon Determinator, Model WR-112.

Soil pH was determined in a 1:1 soil:solution, volume basis (McLean, 1982) with both water and 1N KCl. The samples were allowed to equilibrate one hour before reading the pH.

Exchangeable bases were extracted with 1N ammonium acetate adjusted to pH 7 (Thomas, 1982) and brought to 100-ml volume. Potassium and sodium were determined by means of atomic adsorption on five-fold dilution made with water. Calcium and magnesium were determined by means of atomic adsorption on five-fold dilutions made with a lanthanum solution.

Aluminum was extracted with 1N KCl using a 30 minute extraction time by titration via the NaF method (McLean, 1965).

Effective cation exchange capacity was calculated by taking the sum of ammonium acetate extractable bases and 1N KCl extractable aluminum (McLean, 1965).

Cation exchange capacity was determined using 1N ammonium acetate at pH 7 (SCS, 1972). In general, the soil from below the discontinuity tended to disperse to a much greater extent than the soil from above the discontinuity. This dispersion resulted in very slow leaching rates. There may have also been a problem in the methanol wash. In some instances the methanol may have flowed around the soil mass rather than through it. This would have resulted in incomplete removal of excess NH_4OAC and would therefore have given higher CEC values.

Base saturation was calculated on the basis of either sum of cations or NH_4OAc CEC (SCS, 1972).

Oxalate-extractable iron (McKeague and Day 1966) was measured on a small subset of samples from Sites 9, 11, 13, 15, 19, and 20. The analysis on these samples was done by means of atomic adsorption.

Oxalate-extractable iron, aluminum, and silica (Blakemore et al., 1987) were also measured on samples from Sites 1a and 1b by means of ICP (inductively coupled plasmospectrometer). The extraction was performed by Mrs. Ada Chu, and the analysis was performed by Mr. Ernie

Okazaki. The values for iron from this analysis were about one half that measured by atomic adsorption.

Phosphate retention analysis (Blakemore et al., 1987) was done by Mrs. Ada Chu.

3.2.4 Micromorphological Analysis

Samples from Site 9 were analyzed for their micromorphological characteristics. The samlpes were analyzed by Dr. G. Stoops, Gent University, Belgium. His results and interpretations are presented in Appendix F.

4. RESULTS AND DISCUSSION

4.1 Soils of the Study Area

The soils examined in this study were identified by Foote et al. (1972) as four soil series. From east to west along the transect, the series are Kolekole, Wahiawa, Manana, and Paaloa.

The Kolekole series is mapped at the footslopes of the Waianae Range. According to Foote et al. (1972), these soils are "developed in old gravelly alluvium mixed with volcanic ash" and are classified as Ustoxic Humitropepts. The profile description given in the soil survey indicates a buried horizon (the Waianae fan alluvium) but does not indicate that the overlying soil material consistes of a different parent material.

The Wahiawa series is mapped adjacent to the Kolekole series and extendes across the Wahiawa Basin saddle and up the slopes of the Koolau Range. Foote et al. (1972) considered these soils to have "developed in residuum and old alluvium derived from basic igneous rocks." There is no indication in the profile description in the soil survey that there is a discontinuity present in Wahiawa soils. These soils are classified as Tropeptic Eutrustox.

Soils at Sites 7 and 9 are mapped as the Manana series by Foote et al. (1972). Site 7 is in a small delineation of Manana series near the center of the Wahiawa Basin. Site 9 is adjacent to the fossil stream channel in the Poamoho area. Both of these sites are surrounded by soils mapped as the Wahiawa series. Foote et al. (1972) describe Manana soils as having "developed in material weathered from basic igneous rock." In the discussion of the properties of the Manana series in the soil survey, there is mention of a pan-like sheet but the profile description gives no indication of a discontinuity or buried horizon. Manana soils are classified as Orthoxic Tropohumults.

Soils of the Paaloa series are mapped at high elevations on the leeward side of the Koolau Range. Along this transect, Paaloa soils occur adjacent to and upslope of the Wahiawa Series. Foote et al. (1972) state that Paaloa soils "developed in old alluvium and residuum derived from basic igneous rocks," but in the profile description there is no indication of a change in parent material. These soils are classified as Humoxic Tropohumults.

4.2 Geomorphology

Determination of the mode of formation of the stepped geomorphic surfaces in the Wahiawa Basin was beyond the scope of this study. Because these surfaces may elucidate the formation and distribution of soils, their occurrence is, however, considered here.

In this study, a geomorphic surface is defined as a nearly level to sloping interfluve surface that is bounded by small scarps at its higher and lower elevations. The higher elevation scarp is considered to be part of the same geomorphic surface of the level to sloping land adjacent to and topographically below it.

Arguments presented by Ruhe (1961) point to an erosional origin for the geomorphic surfaces in the Wahiawa Basin. On an erosion surface, the higher scarp is eroded at the same time as the surface below it (see Daniels et al., 1971), whereas the lower scarp is cut into this surface at some later time. The lower surfaces and the soils that formed on them are, therefore, younger than higher elevation surfaces and soils.

As discussed in Section 2.2, the possibility exists that the scarps observed in the Wahiawa Basin were originally constructional (as opposed to erosional) features associated with irregularities of lava surfaces. Wentworth and Winchell (1947) reported that scarps of 2-3 meters high are common on Koolau Volcano and that some scarps are 3-6 meters high. They did not, however, mention the lateral extent of the scarps. Ruhe (1961) outlined his objections to the hypothesis that the scarps in the Wahiawa Basin are constructional features, but his arguments do not preclude the possibility that they were originally constructional features that were later modified by erosion.

The occurrence of surfaces at similar elevations on adjacent interfluves (see Ruhe, 1975, Figs. 7.17 and 7.18) suggests that the surfaces are somehow genetically related. Because the surfaces appear to follow the contours of the southern half of the Wahiawa Basin and because any one surface may occur on two or more lithologies, there is the suggestion that some unifying erosional process was responsible for their formation. In the northern half of the basin, however, the scarps follow the contours and do not appear to cut across different lithologies, and the surfaces all appear to be on the Koolau basalt.

A series of stepped surfaces occurs on alluvium in the Haleanau Gulch drainage in the Schofield Barracks area. It also appears from aerial photos that this stream has the valley within a valley morphology that Ruhe (1961) cited as evidence of multicyclic erosion.

In practice, there was some difficulty in applying the above definition of geomorphic surfaces to the study area. The problem was essentially one of scale and the assumed landscape history. For example, the geomorphic surface below Site 10 is bounded by a scarp normal to the long axis of the interfluve. The next higher surface, however, has a series of small scarps leading from the highest surface down toward the fossil channel (see Fig. 6), but these surfaces become indistinct at lower elevations. These small surfaces were interpreted as benches related to the meandering and downcutting of the stream that occupied the fossil channel. Similar bench-like surfaces were observed along drainageways in the Kunia area. These surfaces are considered to be minor features imposed on the major geomorphic surface.

The sampling sites (Sites 1 through 6) in the Kunia area are on several interfluves but they may be on the same geomorphic surface. They occur on one lithologic unit, the old Waianae fan alluvium.

In the Schofield-Poamoho area, Sites 8 through 20 all occur on basalt. Site 8 is on a knoll that may be a remnant of a former more extensive surface. Sites 9 through 20 are located on two interfluves north of Poamoho Camp. Three surfaces comprise the lower interfluve; four surfaces comprise the higher interfluve (see Fig. 5). Sampling sites were chosen so that there was at least one site on each surface.

On the lower interfluve, surface 1 is separated from surface 2 by a scarp that is more or less normal to the long axis of the interfluve. Surface 3 is in part normal to and in part parallel to the long axis of the interfluve. On surface 2, there are three small scarps between Surface 3 and the edge of the fossil channel. These surfaces are parallel to the fossil channel and are presumably benches cut into the saprolite during the early stage of stream incision.

The scarps separating surfaces on the higher interfluve are all essentially normal to the long axis of the interfluve.

4.3 Stratigraphy

The abrupt, linear boundary indicative of a lithologic discontinuity (Van Wambeke et al., 1983; Arnold, 1968) occurs in several profiles exposed in roadcuts in the Wahiawa Basin. Discontinuities are also exposed along the edges of some interfluves. These discontinuities mark the boundary between overlying transported sediment and a truncated paleo-argillic horizon developed in either alluvium or basaltic residuum. The occurrence of gravel above the discontinuity at Site 13 (and elsewhere in that area) indicates that the discontinuity is an erosion surface. That is, erosion by water truncated soil profiles and created a surface on which eolian and/or alluvial/colluvial sediment was later deposited.

The soils of the study area formed in three distinct layers. The soil below the erosion surface formed in either basaltic residuum or in basaltic alluvium. The soil above the erosion surface consists of two eolian deposits: tropospheric dust from mainland Asia and inferred volcanic ash from a local source. Stratigraphic relationships among landforms, an erosion surface, and the soil above the erosion surface provide the basis for the interpretation that the B horizons of the soil above the erosion surface formed in eolian material. As explained in Section 4.4, identification of resistant minerals by x-ray diffraction analysis was used to correlate the eolian deposit with soils derived from volcanic ash. The stratigraphy of the sediments in the Wahiawa Basin is crucial in establishing the eolian nature of the parent material of these soils, because most of the soils have been so highly weathered that they no longer have the mineralogical, physical, or chemical properties commonly associated with soils formed in volcanic ash.

Photographs of each soil profile (Appendix A), profile descriptions (Appendix B), physical, chemical, and mineralogical data (Appendix C and Appendix D), x-ray diffractograms of representative horizons (Appendix E and Appendix H), and micromorphological descriptions (Appendix F) are included in this report to support the interpretations. The soils data should be viewed from a basin-wide perspective. Interpretations are based on the sum of the evidence, not necessarily on the data from any one profile.

Two geographic areas are distinguished in this discussion of stratigraphy. The Kunia area has soils in which the topsoils have developed in tropospheric dust and the lower part of the solum has formed in old Waianae fan alluvium. The contact with the Waianae alluvium is an erosion surface that truncated a paleosol developed in the alluvium. The B horizons above this lithologic discontinuity have a wide range of characteristics. Some subsoils (Kolekole series) have all the mineralogical, physical, and chemical properties associated with volcanic ash parent materials. On the other end of the spectrum are B horizons with oxic properties (Wahiawa series) and no characteristics of volcanic ash parent material. These two extremes occur within a few hundred meters from each other. Between these extremes are soils (Kunia series) with a suite of highly weathered minerals but also with evidence of volcanic ash. The spatial relationships among the various B horizons, and the relationships among these horizons, the erosion surface, and the interfluves were analyzed to deduce the origins of the various B horizons. Mineralogical analysis was used to correlate the highly weathered B horizons with B horizons developed in volcanic ash.

The soils of the Schofield-Poamoho area also have topsoils formed in tropospheric dust (mixed with subsoil through cultivation at most sites), but the lower part of the solum has formed in basaltic residuum, or alluvium in the fossil channel, from the Koolau Range. An erosion surface has also truncated paleosols on this side of the basin. The B horizons above the erosion surface are characterized by low activity clays and are very similar to one another and to the underlying soil in their physical and chemical properties. Mineralogical data were used to distinguish them from the B horizons developed in basaltic residuum. Stratigraphic relationships among landforms (knolls and a fossil stream channel), the erosion surface, and B horizons above the discontinuity were used to infer an eolian origin of the B horizons above the discontinuity. These B horizons were correlated with soils formed in volcanic ash in the Kunia area via their mineralogical signature with respect to resistant primary minerals.

4.3.1 Kunia Area

The alluvial fans in the Kunia area once had soils developed solely in the alluvium. Remnants of these early soils were evidenced by red clayskins on the brown alluvium. The overlying soil associated with these clayskins was removed when the fans experienced considerable erosion.

At some point in time, there was a change in stream regimen which caused gulches to be cut into the fans. Stearns (Stearns and Vaksvik, 1935) attributed the incision of the fans to a lowering of base level controlled by Koolau streams. In one drip irrigation trench, the erosion surface that truncated the soils that developed in the Waianae alluvium was traced to the bottom of a gulch. The gulch was therefore in place prior to the mantling of the landscape by volcanic ash.

In the present landscape, there are arete-like ridges upslope of some fans (such as the one on which Kunia Camp is located). If the ridges had a similar form at the time of ash deposition, that would preclude the possibility that ash was originally deposited in the Waianae Range, then transported down these ridges to its present location. It would also preclude the possibility that a younger alluvium could have been deposited on the truncated soils developed in the old Waianae alluvium. This latter point is very important, as described in more detail later, in explaining the distribution of the Kunia and Kolekole soil series.

The interfluve north of Kunia Camp, where Sites 2 through 4 are located, has a ridge upslope which could have been a source of colluvium/alluvium. A talus slope at the base of the ridge was mapped as Kunia series (KyC). Site 4, which is the site closest to this potential colluvial source, does not have colluvium but it does have thin lenses of volcanic ash sandwiched between large slabs of Waianae alluvium. Site 2 has clasts of Waianae alluvium within an ash matrix, but it does not have what could be identified as talus. Of all the soils examined on the transect, the soil at Site 3A is most problematical in that it has no evidence of volcanic ash although there are deposits of SRO minerals about 200 m to the south, and 450 m upslope to the west. This soil is the most likely candidate to have a colluvial influence, but it is hard to imagine why this soil would have such a colluvial influence when the soil upslope at Site 2 does not have colluvium.

The elapsed time between erosion surface formation and volcanic ash deposition is not known. There did not appear to be any incipient soil formation in the alluvium below the erosion surface; the patchy clayskins in the alluvium are likely remnants of a previous soil-forming environment. The remnants of soil formation in the alluvium indicates a truncated, buried paleosol (see Ruhe and Daniels, 1958).

The possibility exists that the ash deposition was contemporaneous with the cutting of the erosion surface and that the thick ash mantle inhibited further erosion. There is some evidence for an erosional period between at least two ash deposits. Along Kunia Road, north of Huliwai Gulch, there is a roadcut that exposes ash over an alluvial fan (Fig. 4). There appears to be two ash-derived layers above the old Waianae alluvium, both of which are truncated by the present land surface. A buff-color ash (mapped as the Kolekole series) overlies the alluvium and is truncated and overlain by a red soil layer (mapped as the Kunia series; an admixture of ash and Waianae alluvium?), which also rests on Waianae alluvium. The stratigraphic relationship between the two layers (i.e., separated by an erosion surface) indicates that the buff-color ash was not the parent material for the red soil layer. There are, then, at least two depositional events after the soil developed in Waianae alluvium was truncated. Indications of several erosion/deposition events were also found in the Poamoho area.

A drip irrigation trench system in two interfluves in the Kunia area permitted examination of the stratigraphy there. Site 1 was sampled from a trench on the interfluve south of Kunia Camp; another trench system was located on the interfluve with Kunia Camp. The soils on these interfluves developed in volcanic ash (80 to 120 cm thick) over Waianae fan alluvium. Some of these soils have clasts and slabs (up to 30cm by 200cm in cross section) of alluvium mixed in the lower portion of the ash mantle. These alluvial clasts have the brown color and high bulk density associated with the old Waianae alluvium. They are believed to be derived from the old Waianae alluvium and notfrom some younger alluvium deposited contemporaneously with or later than the volcanic ash.

Figure 4. Exposure of Kolekole series (at left) and Kunia series (at right) along Kunia Road north of Huliwai Gulch. Contact between volcanic ash and old Waianae alluvium at depth of about 1 meter. See text for explanation.

The alluvial clasts in the ash matrix are assumed to be a lag concentrate on the erosion surface. Over time they may have been mixed in with the overlying ash by roots and soil fauna. The large slabs of alluvium within the ash may have fractured from the main body of alluvium when the overburden (soil profile originally developed in the alluvium) was removed by erosion. Ash may have worked its way around the slabs over time as tree roots grew in between slabs and pushed them apart. No mention of these slabs was made by Foote et al. (1972), but they did refer to "earthy lumps" (alluvium clasts?) within the ash layer of the Kolekole series.

At Site 2, a very abrupt, linear boundary separates a buff-color ash mantle from underlying brown alluvium with red cutans. Gravel-size clasts of Waianae alluvium are mixed within a matrix of ash; the number of clasts increases towards the boundary with the alluvium. The clasts are easily distinguished by their hardness (bulk density about 1.6 Mg/m^3 compared with 0.7 Mg/m^3 for ash) and brown color when broken open.

Four parent materials are distinguished at Site 3A. The Ap horizon is influenced by tropospheric dust, the Bw horizons are probably derived partly from volcanic ash, and the 2Bt horizons developed in Waianae alluvium, which is underlain by residual basalt. The alluvium is quite thin here and it pinches out in a few meters north of the sampling location. It is easily distinguished from the overlying Bw horizons by the shiny peds. The alluvium here, however, is much redder than at Site 2 and appears more weathered.

The Bw horizons correlate stratigraphically with the 2Bw horizons developed in volcanic ash upslope at Site 2, but they are apparently more mixed and/or weathered than at Site 2. The boundary between the Bw and 2Bt horizons is very abrupt, and the thickness of soil above the discontinuity is similar to that at Site 2.

Although there is less contrast in color and hardness between the clasts and the Bw matrix than at Site 2, clasts of alluvium (2Bt material) in the Bw horizon can be distinguished by their rounded shape, high bulk density, and by their brown color when broken open. The matrix of the Bw horizons, however, does not resemble the ash found at Site 2 in its color, mineralogy, or bulk density. The bulk density is quite high at about 1.3 Mg/m^3 and the x-ray diffraction analysis does not indicate any more SRO minerals than are in the Waianae alluvium. Although the cause of the differences in the soil above the discontinuity between Sites 2 and 3 is not clear, their proximity and prominent discontinuities indicate that the stratigraphy is essentially the same at both sites: volcanic ash mixed with alluvium clasts over old Waianae alluvium.

The soil (mapped as the Kunia series) that is exposed along Kunia Road across the street from Kunia Camp, and a few tens of meters south of Site 3A, also has a very distinct discontinuity. Visually, the soil above the discontinuity more closely resembles ash than it resembles the oxic horizons so common in the Wahiawa area, but the soil above the discontinuity does not have appreciable amounts of SRO minerals. On the otherhand, just a few tens of meters east of this site, on a slope leading into the gulch north of Kunia Camp, there is a lens of soil (Site 3C) that gave an x-ray diffraction pattern similar to the B horizons developed in ash at Site 2.

It seems improbable that high SROM soil such as the 2Bw horizons of Site 2 could have been deposited at the same time as the Bw horizons of Site 3A which have a highly weathered mineral suite. Yet, the stratigraphic evidence points to this interpretation. Both sites are on the same interfluve and also appear to be on the same geomorphic surface. The 3BCt horizons of Site 2 and the 2Bt horizons of Site 3A are the remnants of an argillic horizon developed in the Waianae alluvium. From a stratigraphic viewpoint, it seems reasonable that deposits on the same erosion surface, separated by only a few hundred meters, are the same deposit.

The sequence of Kolekole-Kunia-Wahiawa series seems to represent the transition from the least to the most highly weathered volcanic ash. The Kolekole soil at Site 2 has readily identifiable clasts of Waianae alluvium within a matrix of SROM soil material. The Kunia soil exposed along Kunia Road at Kunia Camp retains an ash-like morphology and has abundant alluvium clasts, but there is little evidence of SRO minerals. The Wahiawa soil at Site 3A also contains clasts of Waianae alluvium but the soil matrix has neither the morphology nor the mineralogy indicative of a volcanic ash parent material.

The stratigraphy of the Kunia series indicates that the alleged alluvium/colluvium of these soils was deposited after the volcanic ash parent material of the Kolekole series was deposited. An auger hole was dug near the intersection of Kolekole, Kunia, and Wahiawa series delineations (Site 3B, Fig. 2). The B horizons above the Waianae alluvium resemble the Kunia series subsoil except for an 8 cm thick, red ashy soil immediately above the Waianae alluvium. This ashy soil was the only sample taken from this auger hole. The x-ray diffractogram of this sample showed that the soil is highly weathered (high gibbsite content), but it still has a significant amount of SRO minerals and has only very small amounts of magnetite and ilmenite. As explained later, the results of this study indicate that small amounts of these minerals characterize volcanic ash in the Wahiawa Basin. This sample appears to have had a volcanic ash parent material. The overlying soil does not resemble ash in the field, and, assuming that it is a separate geologic layer, it must have been deposited after the ash.

In the Kunia Camp area, the Kolekole series covers the breadth of the interfluve (as confirmed through examination of drip irrigation trenches) and Kunia soils (exposed along Kunia Road) occur downslope. It seemed improbable that alluvium (Kunia series) would be deposited downslope of volcanic ash (Kolekole series) without leaving a trace of alluvium in the ash, although it is conceivable that alluvium could have been deposited on top of the ash and then later eroded.

If, however, the highly dissected landscape upslope of the Kunia Camp interfluve were in place at the time of ash deposition, then the volcanic ash upslope of Kunia Road would have been the only parent material available for the Kunia series downslope of Kunia Camp. The differences between Kolekole and Kunia series are, therefore, not due to parent material differences (ash versus alluvium) but are due to different stages of weathering of the volcanic ash.

The soil at Site 4 is mapped as the Kunia series. This profile consists of an A horizon over thin layers of volcanic ash between several slabs of Waianae alluvium. Because of the slabs of alluvium, it is assumed that this profile is probably not representative of the majority of Kunia soils in this delineation. The other soils in this delineation are assumed to have a greater degree of mixing of ash and alluvium. The important point here is that the volcanic ash occurs at the contact with Waianae alluvium in a delineation of Kunia soils. If it is assumed that the Kunia Bw horizons formed in a different parent material than did Kolekole Bw horizons, this indicates that the ash deposition predates the alleged alluvium/colluvium parent material of the Kunia series.

This argument assumes that the Kolekole and Kunia series formed from two distinctly different parent materials: volcanic ash and alluvium/colluvium. As explained earlier, the stratigraphy is more consistent if viewed from the perspective that the subsoil of these two series formed in basically the same parent material (volcanic ash with some mixing of Waianae alluvium), and the differences in the soils are mainly due to different degrees of weathering and/or mixing with old Waianae fan alluvium.

Site 5 was located in a delineation of Helemano series and is downslope of a large delineation of Kunia series. This soil consists of volcanic ash mixed among slabs and clasts of old Waianae alluvium.

Site 6 was located near the boundary between the Waianae fan alluvium and Koolau basalt (Stearns and Vaksvik, 1935, Plate II). The profile at this site has about a meter of soil above a discontinuity. It was difficult to identify the material immediately below the discontinuity, but it appears to be a thin (about 50 cm) layer of old Waianae alluvium over residual basalt.

4.3.2 Poamoho Area

Site 7 was on the eastern side of a small knoll at the junction of Kunia Road and Wilikina Drive, which is almost the exact center of the basin divide. On the Schofield Barracks Quadrangle (USGS, 1953b) this knoll is indicated by the 880 foot contour line. Basaltic residuum occurs below a prominent discontinuity in this soil profile. Given that this knoll forms a local high point in the landscape, the soil above the discontinuity is probably an eolian deposit. As explained later, the mineralogy of the soil developed in this eolian deposit indicates that the parent material is probably volcanic ash.

Site 8 in the Poamoho area is similar to Site 7 in that it also occurs on a knoll. This knoll at the junction of Kaukonahua Road and Kamehameha Highway is indicated by the 980 foot contour line on the Haleiwa Quadrangle (USGS, 1960). As with Site 7, there is over a meter of soil above a discontinuity with basaltic residuum. The interpretation of this soil profile is the same as for Site 7: eolian material covers an erosion surface at a high point in the landscape. The mineralogy also indicated a volcanic ash parent material for the eolian deposit.

Site 8 appears to have several discontinuities. A lower discontinuity cut into Koolau basalt, as evidenced by the large boulders, while an upper discontinuity separates red soil from a topsoil layer that appears to be buried by a plow berm. There may also have been another minor discontinuity in the upper 30 cm of the red soil. If so, do these two layers of red soil represent two ash deposits? This soil occurs on a small knoll, so it is not in a position where it could accumulate slopewash sediment.

The Poamoho study area also consists of two adjacent interfluves that are bordered by Poamoho Gulch on their south side. On the northern side of the higher interfluve is an unnamed tributary which flows into Poamoho Stream and separates the two interfluves. Prior to capture by Poamoho Stream this unnamed tributary once flowed on the northern side of the lower interfluve. The stream's former channel is now a fossil channel which forms a 15-meter deep hanging valley about 50 meters higher than the channel of the unnamed tributary. Water from Upper Helemano Ditch is channeled into this former channel to form the Upper Helemano Reservoir.

Meandering by both streams progressively narrowed the one long interfluve until the unnamed tributary incised the fossil channel to the depth seen today. At that time the land bridge connecting the two interfluves was breached, thus isolating the lower interfluve. The higher interfluve was also isolated due to stream dissection of the upslope terrain, but there is no evidence to indicate when that happened.

The stratigraphy of the lower interfluve in the Koolau study area was revealed in a series of trenches dug for drip irrigation water mains. These trenches traversed all geomorphic surfaces on the lower interfluve, and one of the lines extended to the floor of the fossil channel adjacent to the northern side of the interfluve. Depths of the trenches ranged from 90 to 150 cm.

The soils that were exposed in these trenches are similar to those on the Waianae side of the basin in that most profiles contain a prominent discontinuity. The discontinuity occurs at depths ranging from 60 to 95 cm, and it is a nearly uninterrupted feature across the landscape. In some areas the discontinuity was not visible. It appeared to extend below the trench floor in places; in other areas it may have been destroyed by mixing and/or weathering.

The scarps separating geomorphic surfaces were examined for evidence of alluvium and cut/fill relationships. Given the working hypothesis that the surfaces are erosion surfaces, evidence of erosion or alluvial deposition were expected. No trace of water-laid sediment, however, was found near the scarp separating Surfaces 1 and 2 (Fig. 5). Small areas of alluvium were found above the discontinuity on the hillslope leading into the fossil channel. No alluvium was associated with the minor scarps on Surface 2 which, as described earlier, are thought to be benches cut by the stream that formerly flowed through the fossil channel.

The discontinuity can be traced continuously from the highest geomorphic surface to the floor of the fossil channel (Fig. 6). On the interfluve upland, the discontinuity is underlain by soil

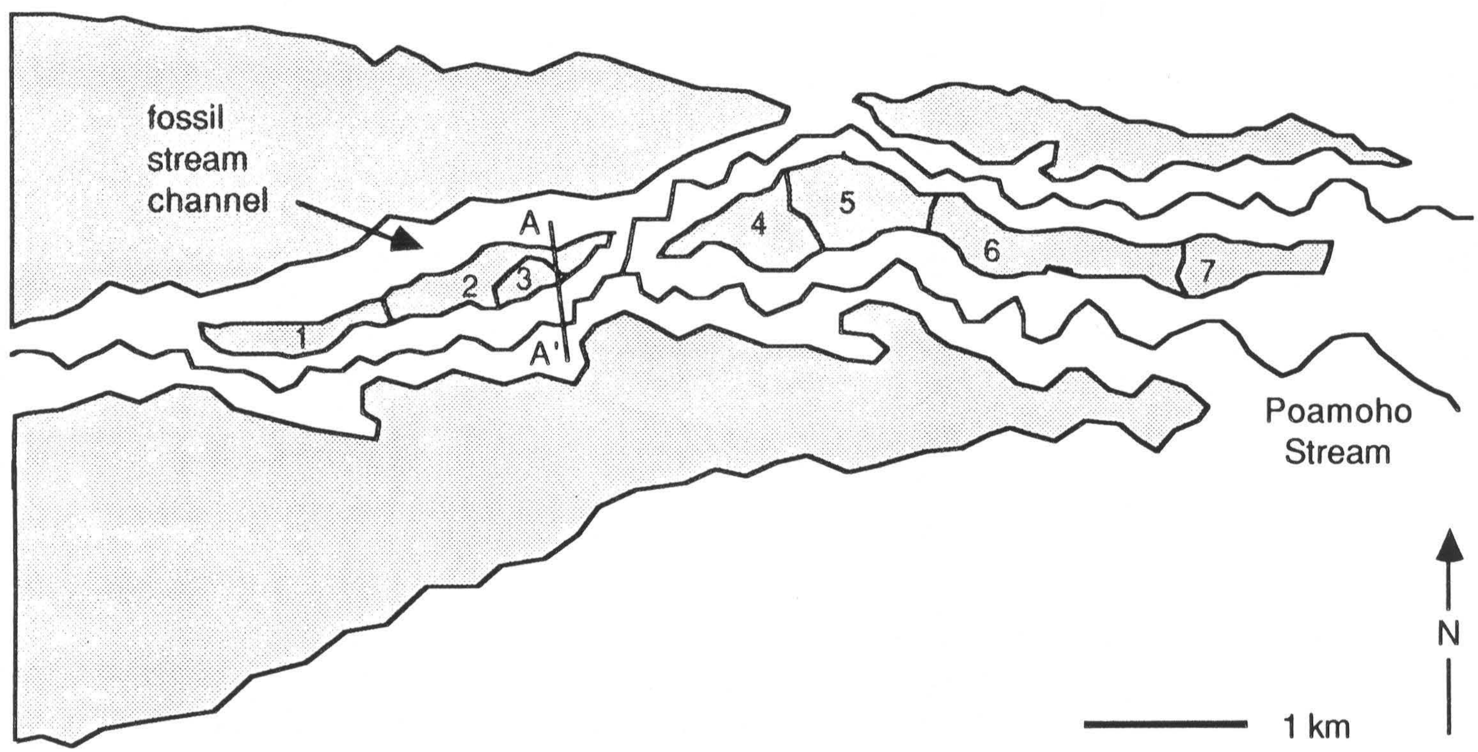

Figure 5. Plan view of the Poamoho area showing relationships among interfluves (shaded areas), fossil stream channel, and Poamoho Stream. Cross-section A-A′ is shown in Figure 6. Numbers on interfluves refer to geomorphic surfaces; see text for explanation.

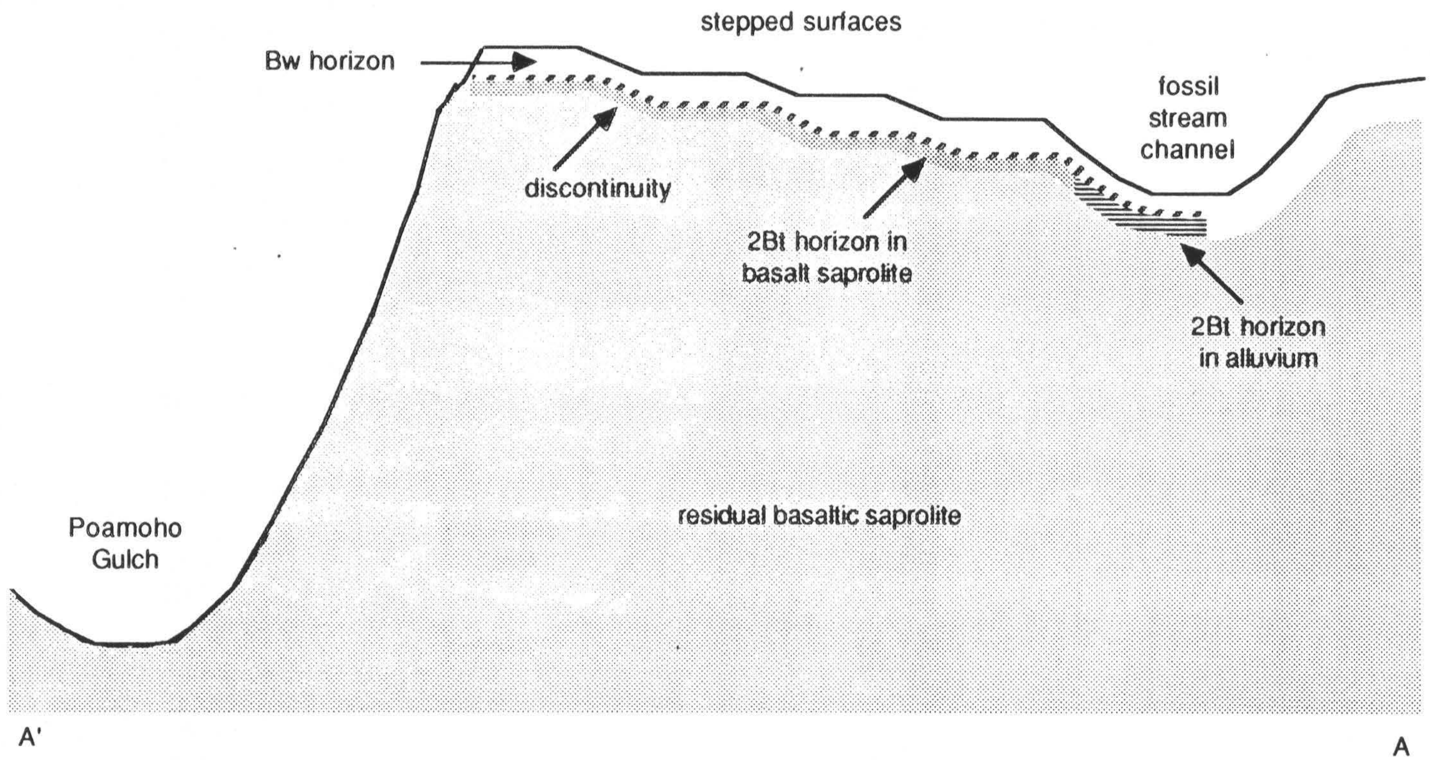

Figure 6. Cross-section A-A′ of lower interfluve in the Poamoho area showing the relationships among the stepped surfaces, discontinuity, and fossil stream channel. See Fig. 5 for location. No scale.

developed in residual Koolau basalt. The same discontinuity was traced into the fossil stream channel, but there the discontinuity was underlain by Koolau basaltic alluvium. The hillslope leading into the fossil channel was examined to find the facies change between residual basalt and alluvium, but the transition zone was not located.

A very small lens of alluvium (Site 13) was found above the discontinuity on Surface 2 and on the hillslope to the fossil channel. This clearly indicates that the discontinuity is an erosion surface, not a pedogenic feature, and that the soil above the discontinuity is transported material. From Site 13, the same discontinuity can be traced in the trenches for the full length of interfluve, across all geomorphic surfaces. The implication is that all soil above the discontinuity on this interfluve developed in transported material.

Features associated with discontinuities (abrupt, linear boundaries) occur in the profiles exposed in the trench in the fossil channel (Site 14). Although there are two discontinuities, the soil above them may not necessarily represent two eolian layers. The topographic position of the site is such that sediment could have been deposited from upslope.

The continuous nature of both the erosion surface and the soil profile (i.e., no cut/fill structures at scarps separating surfaces) suggests three things: (1) at one time, soil profiles over the length of this interfluve were truncated and the erosion surface was exposed to subaerial processes (i.e., weathering, erosion, deposition); (2) the same erosion surface was contemporaneous on all geomorphic surfaces, so the geomorphic surfaces are all the same age; and (3) the soil material above the discontinuity is the same age on all surfaces and younger than the discontinuity itself. All of these points are contrary to the interpretations of Ruhe (1975, pp. 142-148) regarding the age relations among soils and surfaces. The differences among soils on different geomorphic surfaces are therefore not due to differences in age. The thickness of parent material above the discontinuity and the variations in climate (most likely former climates) across the landscape were probaby the main factors that influenced soils distribution.

An erosion surface is younger than any deposit that it cuts (Ruhe, 1975, p. 223). Alluvial deposits on the floor of the fossil channel are, therefore, the same age as or younger than this former stream channel. The erosion surface that extended from the highest point on the interfluve (Site 11) to the floor of the fossil channel cut alluvial deposits (the 3Bt horizons, Site 14) on the floor of the former stream channel. The erosion surface, therefore, is younger than the alluvium and the channel.

The erosion surface in the fossil channel has no overlying alluvium and, therefore, probably postdates the capture of the unnamed tributary by Poamoho Stream. Otherwise, if the fossil channel was still connected with the unnamed tributary, there would have been alluvium deposited on this erosion surface. There was, then, no soil material above the discontinuity after the interfluve was isolated from adjacent interfluves. In this scenario, no significant amount of alluvium could be deposited above the discontinuity on the highest geomorphic surface (Site 11) since there was no upslope source. Only an eolian material could traverse the gulches that surrounded the interfluve. As explained later, this eolian material is suspected of being volcanic ash. There are, then, two eolian deposits in the soils on this interfluve: tropospheric dust which forms the A horizons, and a volcanic ash deposit which forms the B horizons above the erosion surface.

The hypothesis of a mantle of local eolian material is consistent with the stratigraphy of the lower interfluve. Given the short length of the interfluve, an eolian deposit would blanket all geomorphic surfaces with a more or less uniform depth of material; sediment thickness above the discontinuity was observed to be nearly the same across the interfluve. An eolian origin is also consistent with the lack of alluvial deposits (for the most part) above the discontinuity, and the lack of cut/fill relationships at the scarps between geomorphic surfaces. Mantle bedding and a lack of alluvial structures are two of the criteria cited by Wentworth (1926, p. 74) as characteristic of pyroclastic deposits.

The age of the eolian B horizons is post-erosional because the layer in which they developed mantles the fossil stream channel. That is, the eolian mantle was deposited after quiescence and subsequent erosion of Koolau Volcano. This is circumstantial evidence that the eolian deposit belongs to either the Kolekole or the Honolulu Volcanics; i.e., the B horizons above the discontinuity developed in volcanic ash.

If the erosion surface existed prior to the isolation of the lower interfluve (Sites 9-14), then the possibility that the soil above the discontinuity developed in alluvium cannot be discounted. This scenario, however, seems unlikely for several reasons. An alluvial deposit would likely leave widespread evidence of stratification, yet only very small areas of thin alluvium were found in upland positions. Any alluvium would necessarily originate upslope and have to pass through a relatively narrow land bridge before spreading over three geomorphic surfaces that extend for a total length of 2.5 kilometers. The alluvium would also have to spread out perpendicular to its main direction of flow to cover parts of the fossil channel, and it would be distributed so as to produce a nearly uniformly thick mantle that covered both steep slopes and nearly level ground.

The above alluvial scenario is contingent upon a source of sediment upslope. The higher adjacent interfluve that would have been the alluvial source was examined through six pits and one roadcut (Sites 15-20). An erosion surface (in all likelihood the same one seen on the lower interfluve) was exposed at the western tip of this interfluve. A discontinuity was observed in four of six pits and in the roadcut (data presented later shows that the discontinuity can be detected via mineralogy in the pits that did not have abrupt boundaries indicative of a discontinuity). It seems reasonable to assume that this interfluve was also devoid of a soil mantle at the same time that the lower one was, and was therefore not a sediment source.

The truncation of soil profiles over whole interfluves also occurred on the Waianae alluvial fans. Was profile truncation contemporaneous on both sides of the basin and in response to the same conditions? If the events were not contemporaneous (the "non-contemporaneous" model referred to hereafter), then there must have been at least two erosional events with each one primarily affecting only one side of the basin.

Based on the greater degree of soil development in the eastern and central parts of the basin, the most likely scenario in the "non-contemporaneous" model would be that the entire basin was denuded of soil, then an volcanic ash was deposited on the erosion surface. This volcanic ash was then weathered into soil and there was the concurrent accumulation of tropospheric dust to form a topsoil. Then, after a highly weathered soil had formed, there was extensive erosion on the western side of the basin and a new erosion surface (or an exhumed erosion surface) was on the Waianae alluvial fans. A relatively recent layer of volcanic ash was then deposited on this erosion surface. In this model, only those areas now mapped as Kolekole soils were eroded to the extent that the earlier volcanic ash layer above the discontinuity was completely removed.

Two problems with the "non-contemporaneous" model are: (1), Why would only parts (areas mapped as Kolekole soil) of some interfluves be eroded to such an extent?; and (2), Why were traces of the volcanic ash that formed the Kolekole soils not found on the surfaces of adjacent older soils? The distribution of Kolekole soils as mapped by Foote et al. (1972) does not lend itself to a convenient answer with regards to the erosion question. As for the latter question, could it be that the ash, which is close to a meter thick in Kolekole soils, was simply eroded in other locations so that no trace of it is left, even in adjacent soils? Although the soils shown in Fig. 4 show evidence of several erosional events, this scenario seems improbable because the topsoils formed in tropospheric dust are essentially the same thickness in the Kolekole, Kunia, and Wahiawa series. The similar thickness of the topsoils implies that the topsoils have been accumulating the tropospheric dust for the same amount of time and are, therefore, the same age.

The other option to explain these soils is the "contemporaneous" model in which the erosion surface found across the basin is the same age everywhere, and there is basically only one eolian deposit which covers this surface. As explained earlier, the stratigraphy and distribution of SROM soil material seem to favor this interpretation.

A discontinuity also occurs in the low elevation Oxisols above the Pearl Harbor area. If the soil above the discontinuity is the same as that found above the discontinuity at higher elevations, then it would be possible to give a relative date for the deposition of the eolian derived soil above the discontinuity. The relationship between the eolian derived soil and the Keana and Waimanalo sea levels could provide a date relative to one of these former high stands of the sea. Because soils with deep, red oxic horizons are not mapped (Foote et al., 1972) below the Kaena (+30 m) shoreline, the preliminary interpretation is that the soil above the discontinuity was deposited prior to the Kaena stand of the sea (ca. 500,000 ka). Detailed field investigations would be required to support this interpretation.

4.4 Mineralogical Analysis

X-ray diffraction analysis was used to identify soil minerals at all sites along the transect. Analysis of the clay fraction revealed some differences in mineral contents in the soil above and below the discontinuity. There were few indications of SRO (short-range order) minerals, however, except for samples from the Kolekole series and a few other samples that were obviously derived from volcanic ash. Data from the analysis of the clay fraction are not presented in this report.

Analysis of bulk powder samples (silt plus clay fraction) revealed a pattern not observed in the analysis of the clay fraction. The B horizons above the erosion surface in both the Kunia and the Schofield-Poamoho areas contained noticeably less magnetite and ilmenite than either the tropospheric dust or the soils developed in Waianae alluvium and Koolau basalt and alluvium. Because of their particle size and/or particle density, apparently neither of these minerals was in the clay fraction.

A number of samples of lavas from the lower, middle, and upper members of the Waianae Volcanics were analyzed microscopically by Macdonald (1940). He reported a range of 4 to 20% ores (magnetite plus ilmenite), with 10% ores being most common. Macdonald also examined two samples of vitric tuff from the upper member of the Waianae Volcanics (now considered to be Kolekole Volcanics) but did not mention the occurrence of ores in either sample.

Wentworth and Winchell (1947) reported that ore minerals, as variable proportions of magnetite and ilmenite, occur in all Koolau lavas. They stated that ore minerals are usually associated with the granular groundmass of lavas, but magnetite was reported to occur as inclusions in olivine phenocrysts and as dust-like particles in glass. They interpreted this to mean that magnetite formation occurred from very early to very late stages in the crystallization of magmas.

Winchell (1947) found an average of about 5% ores (opaque minerals) in 29 basalt samples of the Honolulu Volcanics. The ores generally consisted of more magnetite than ilmenite. Only 3 of 29 samples of lavas did not contain ores. This contrasted with the tuff samples in which only six of ten samples had even traces of ores. These tuff samples had been sampled close to their sources, so the sorting out of heavy minerals with increasing distance from the source does not account for their absence in these tuffs. The pyroclastics of the Honolulu Volcanics apparently had, for some reason, very small amounts of magnetite and ilmenite relative to basalts of the Honolulu Volcanics. The small amounts of opaque minerals in pyroclastics of the Honolulu Volcanics may be due to rapid cooling of the magma before the crystallization of the opaque minerals (Walker, personal communication, 1989).

Wentworth (1926) described the magnetite contents of 14 "black ash" samples of the Honolulu Volcanics. His descriptions of the magnetite contents of these ashes ranged from "considerable magnetite" to "little or no magnetite." However, his description of a generalized ash on Oahu was that it had "much magnetite in the form of irregular grains." Wentworth did not review pyroclastic deposits associated with the Waianae Volcano.

Stearns (Stearns and Vaksvik, 1935) reported that petrographic analyses were done for pyroclastic deposits on Oahu, but he only presented general descriptions of the mineralogy. Stearns did not thoroughly review the distribution of pyroclastic deposits on Oahu.

The picture that emerges is that basalts of the Waianae, Koolau, and Honolulu Volcanics generally contain at least several percent opaque minerals. The limited published data on the mineralogy of pyroclastics on Oahu indicate that ore minerals are either absent or occur in very small amounts in these deposits. Results from the present study reinforce these views. All of the soil samples derived from basalts contained magnetite and most contained ilmenite, but generally with smaller amounts of ilmenite than magnetite. Soils with large amounts of SRO minerals (volcanic ash) usually contained very small amounts of both magnetite and ilmenite. Some of these soils had such small amounts of these resistant minerals that they could not be detected by x-ray diffraction above the background noise. Stirring a magnet through dispersed ash samples revealed that there are some magnetic minerals (both magnetite and ilmenite) in the ash, although the quantity is quite small.

In both the Kunia and the Schofield-Poamoho areas, the highly weathered B horizons above the discontinuity lacked the physical or chemical properties characteristic of volcanic ash. These B horizons were distinguished from the truncated paleosols below the discontinuity by their very small amounts of magnetite and ilmenite. This signature of resistant mineral quantities was used to correlate these horizons with the soils developed in volcanic ash in the Kunia area.

The influence of tropospheric dust on the soils of the Wahiawa Basin is evidenced by the presence of quartz. Jackson et al. (1971) reported an abrupt transition from the high quartz content topsoils of the Paaloa series to the relatively low quartz content topsoils of the Wahiawa series. Their explanation of this observation was that the Wahiawa series may have experienced more erosion than the Paaloa series. The observations of Jackson et al. are not supported by the present study. Although there is indeed a decrease in the quartz content of topsoils along a precipitation gradient, an abrupt transition in the quartz content between the Paaloa and Wahiawa series was not observed.

Mica is also frequently mentioned in the literature as being deposited along with quartz, but the sample preparation employed was not conducive to the detection of mica. P. F. Fan (personal communication in Montagne, 1970, p. 71) speculated that the rutile in Hawaii topsoils may have an eolian origin. This is the only mention of a mineral other than quartz and mica in the literature on the tropospheric dust in Hawaii.

Minerals other than quartz that appear to be associated with the tropospheric dust are magnetite, ilmenite, anatase, rutile, and pseudobrookite. Walker et al. (1969) speculated that all of these minerals were forming in place through precipitation. They also thought it unlikely that dust from a continental source could account for the presence of quartz. Montagne (1970) concluded that the quartz probably did have an eolian origin. Her review of the literature on the formation of ilmenite, pseudobrookite, and rutile led her to conclude that none of these minerals formed by precipitation. She concluded that residual enrichment by means of erosion of fine sized material from post-erosioanl pyroclastics was responsible for the accumulation of ilmenite, pseudobrookite, rutile, and quartz in topsoils.

Bricker and Prospero (1969) reported that tropospheric dust from an African source is accumulating in the Bermuda Islands and Barbados. This dust consists primarily of quartz and smaller quantities of chlorite, muscovite, kaolinite, feldspar, smectite, and calcite.

Results of the present study strongly suggest that minerals other than quartz and mica comprise the tropospheric dust in Hawaii. X-ray diffraction analysis of relatively unmixed tropospheric dust deposits shows a suite of resistant minerals not detected in the volcanic ash parent material. Of principal interest to this study are the occurrence of magnetite and ilmenite in the dust deposits. Some high elevation sites on the transect contain very large amounts of both quartz and ilmenite. Generally, there is noticeably more magnetite and ilmenite in the topsoils as compared with the eolian B horizons. There are also secondary minerals in the tropospheric dust deposits, but this study did not attempt to determine whether they were formed *in situ* or were also components of the dust.

In summary, the trend in the relative magnetite and ilmenite contents of the modal profile on the transect is high content in the tropospheric dust, low content in the eolian B horizon developed in volcanic ash, and high content in the truncated soil developed in basaltic residuum and alluvium. Some mixing of high ore content material has undoubtedly contaminated the soils developed in volcanic ash. It is quite remarkable that distinct differences in the mineralogy of strata still exist.

As pointed out by Wentworth (1926, p. 18), on Oahu, there are difficulties associated with recognizing volcanic ash deposits some distance from their source. From the standpoint of the present study, the most notable difficulty is that the chemical compositions of ash and basalt are very similar. The prolonged weathering of the two parent materials can produce nearly identical end products. Eswaran and DeConinck (1971) reported kaolinite, halloysite, gibbsite, goethite, hematite, quartz, montmorillonite, and amorphous iron in soils developed in basalt in Nicaragua and Madagascar. On the island of Hawaii, Hudnall (1977) reported the occurrence of smectite, hydrated gels, halloysite, gibbsite, and iron oxides and hydroxides in soils developed in volcanic ash. Naidu et al. (1987) reported kaolin, feldspar, goethite, and gibbsite in soils developed in volcanic ash in Fiji.

4.4.1 Kunia Area

The A horizons of the soils in the Kunia area are all influenced by the addition of tropospheric dust as evidenced by the large quartz contents. Some B horizons also show some quartz, but this is only a small fraction of what is found in the A horizons. The quartz in the

B horizons is an indication of the degree of mixing of these horizons with the topsoil.

Sites 2 and 4 are located along the edges of gulches and have probably never been plowed. At Site 2, samples were taken from 2 cm on either side of the contact between the A and B horizons. These samples show that some quartz has been mixed into the B horizon (volcanic ash). The A horizon also has a relatively moderate amount of magnetite and a small amount of ilmenite. In the B horizon, the magnetite peak cannot be distinguished from the background noise, but there is a trace of ilmenite. The SRO minerals predominate in the B horizon but were not identified in the A horizon.

The point of the above discussion is that there appears to be mixing from the A horizon down into the B horizon, but not vice versa. The minerals in the A horizons are, therefore, not derived from the B horizon.

The Bw horizons of the Kolekole series (Sites 1 and 2) are characterized by large amounts of SRO minerals. On the x-ray diffractograms this is indicated by the high intensity of the background noise, and by the broad, strong peak at about 3.3 A (Wada, 1977).

Some horizons in soils other than Kolekole series also display these characteristics. Just a few tens of meters to the southeast of Site 3A, at Site 3C, on a slope leading into the gulch north of Kunia Camp, is a lens of soil that gives an x-ray a diffraction pattern similar to the Bw horizons at Site 2. At Site 3B, about 200 m upslope of Site 3A, there is a horizon of high SROM soil immediately above the old Waianae alluvium. This horizon also contains many highly weathered crystalline minerals and is overlain by highly weathered soil identified as the Kunia series.

High SROM horizons are sandwiched among slabs and clasts of old Waianae alluvium at Sites 4 and 5. About 30 meters north of Site 6, near the floor of Waikele Gulch, a sample of high SROM soil was collected from above the erosion surface cut into fractured basalt. This sampled contains the largest amount of SRO minerals, and least amount of crystalline minerals, of any analyzed sample from the Wahiawa Basin. Analysis by means of transmission electron microscopy (TEM) reveals only a few crystalline minerals, and no imogolite. Most of the material in this sample appear to be gels, but allophane could be present. The preservation of the SRO minerals may be related to protection of this soil afforded by an overlying rock.

The high SROM soils referred to above all developed in volcanic ash. This interpretation is based on the combination of stratigraphic evidence, x-ray analysis, and chemical and physical properties that meet the definition of andic properties (Soil Survey Staff, 1987).

Wada and Wada (1976) reported on the clay mineralogy of one Bw horizon of the Kolekole Series and found little evidence of volcanic ash. According to Kanehiro (personal communication, 1987), they collected their sample from the roadcut along Kunia Road just north of Huliwai Gulch (see Fig. 4). This exposure of the Kolekole series has considerably more alluvial clasts mixed into the ash layer than does the Kolekole soil examined in this study. X-ray diffraction analysis of samples from this roadcut basically agrees with the results of Wada and Wada. Although this soil has an ash-like morphology, the mineralogy appears to have been transformed into predominately crystalline minerals. It is likely that the sample of Wada and Wada may have been a mixture of the ash and the alluvial clasts.

Allophane and imogolite were reported to have formed from basaltic saprolite on Maui (Wada et al. 1972), occurring as fillings and coatings in vesicles and cracks. Small amounts of SRO minerals occur in a basaltic saprolite boulder at Site 6, but there is no concentration of these minerals as found in the ash-derived horizons of the Kolekole soils. In addition to the SRO minerals, there is also a large amount of ilmenite and a small amount of magnetite in this boulder. The argument that the SRO minerals of the Kolekole series could be derived from basalt weathering seems untenable because the Kolekole Bw horizons have only traces of magnetite and ilmenite. There are two other problems with the hypothesis that the SRO minerals of the Kolekole series were derived from basalt weathering: (1) the hypothesis requires a sorting process to separate most of the crystalline secondary minerals from the SRO minerals; and (2) it seems unlikely that any alluvial material could have been deposited above the discontinuity on the Waianae alluvial fans because the highly dissected landscape was already in place upslope.

The ash-derived Bw horizons at Sites 1, 2, and 5 all have very small or nondetectable amounts of magnetite and ilmenite. The profiles at these sites also share a trend with respect to crystalline and SRO minerals. The Bw horizons nearest the surface have the largest amounts of crystalline minerals and smallest amounts of SRO minerals. With increasing depth, however, the crystalline minerals decrease while the SRO minerals increase. It appears, therefore, that the crystalline minerals (kaolin, hematite, and goethite) formed at the expense of the SRO minerals.

Soils with highly weathered B horizons with only trace amounts of SRO minerals also occur in the Kunia area. The x-ray diffractograms of the Bw horizons at Site 3A, about 450 meters downslope of Site 2, do not show any trace of SRO minerals but do show a fair amount of magnetite and a small amount of ilmenite. Actually, this is the only profile with Bw horizons having nearly the same amount of resistant minerals as the underlying 2Bt horizons.

The Bw horizon sampled at Site 6 contain a small amount of magnetite and a trace of ilmenite, but the 2Bt horizon has considerably greater amounts of both minerals. In addition, the magnetite peak for the Bw horizon is relatively broad, indicating a very small particle size, whereas the magnetite peak for the 2Bt horizon is quite sharp, indicating a large particle size. This difference in particle size may be an indication of different conditions at the time of crystallization.

The truncated soils (2Bt horizons) at all sites in the Kunia area formed in old Waianae fan alluvium, and they all have very similar mineralogical signatures. Horizons developed in alluvium have appreciable amounts of kaolin, goethite, hematite, magnetite, and variable amounts of gibbsite and ilmenite. There is little or no indication of SRO minerals.

The trend of magnetite and ilmenite contents is high in the tropospheric dust, low in volcanic ash, and high in basalt-derived alluvium at all sites in the Kunia area. This trend is least well expressed at Site 3A. An attempt was made to quantify the relationships in the amounts of these resistant minerals in the three parent materials. The Voigt area (see Methods of Analysis) was calculated for the magnetite and ilmenite peaks in the A1 (tropospheric dust), 2Bw3 (volcanic ash), and 3BCt (Waianae alluvium) horizons at Site 2. The values for magnetite (m) and ilmenite (i) for the three horizons are: A1, 7 (m) and 27 (i); 2Bw3, nondetectable amounts of both minerals; 3BCt, 13 (m) and 30 (i). These values can be used comparatively. Thus, the 3BCt horizon contains about twice as much magnetite as does the A1 horizon, and both horizons have about the same amount of ilmenite. The soil formed in volcanic ash is distinctive in having nondetectable amounts of both minerals.

4.4.2 Schofield-Poamoho Area

Although four soil series (Wahiawa, Paaloa, Manana, and Kolekole) are mapped in this area, they probably all have the same parent material. The soil at Site 8 is incorrectly identified as the Kolekole series by Foote et al. (1972). Except for low magnetite and ilmenite contents, the soil above the discontinuity does not resemble the Kolekole series in the Kunia area in morphology, in mineralogy, or in physical and chemical properties. Other delineations of Kolekole series in this area are probably also incorrectly identified and they should be mapped as either Wahiawa or Manana series.

The mineralogy of the A horizons in the Schofield-Poamoho area is basically the same as that of the A horizons in the Kunia area which developed in the tropospheric dust. There are, however, three notable exceptions: a buried, unmixed A horizon at Site 13, and two relatively unmixed A horizons at Sites 19 and 20. These unmixed horizons contained very large amounts of quartz and ilmenite.

At Site 13, the buried A horizon that developed in the tropospheric dust does not appear to be mixed to any significant degree with locally derived soil. The minerals identified in the Ab horizon are: chlorite and/or mica, kaolinite/dehydrated halloysite, gibbsite, goethite, quartz, anatase, brookite, rutile, ilmenite, maghemite, and hematite. Magnetite was not identified in this horizon and it may be that it was converted to maghemite *in situ*.

Sites 19 and 20 occur in high rainfall, watershed land so there is no evidence of plowing, but there has been a small amount of disturbance due to military exercises. The mineralogy of the A horizons is nearly the same as the Ab horizon at Site 13, except for a small amount of magnetite at these high elevation sites.

Being relatively unmixed with locally derived soil, the suites of minerals in the tropospheric dust deposits at Sites 13, 19, and 20 may represent the original components of the dust. On the other hand, some of the minerals could be authigenic minerals formed *in situ*. Although mainland Asia (Gobi Desert?) has been cited as the source of the tropospheric dust in Hawaii (Rex et al., 1969; Clayton et al., 1972), no study has attempted to demonstrate that continental Asia is indeed the source. Without knowledge of the regional source of the tropospheric dust, and therefore no knowledge of the minerals available for eolian transport, an Asian source cannot be ruled out for the secondary minerals found in the dust in Hawaii.

Sites 17 and 18 (plowed) and Site 19 (unplowed) are very close to each other and they probably have received similar amounts of rainfall and tropospheric dust. The quartz contents from all three sites are comparable, but they have very different ilmenite contents. Where the tropospheric dust is mixed with oxidic B horizons by plowing, the ilmenite contents are much lower than would be expected given the quartz contents. Perhaps, the detection of ilmenite is somewhat masked by the oxidic minerals, whereas the detection of quartz is not affected in a similar manner.

The B horizons above the discontinuity in the Schofield-Poamoho area are all highly weathered and show little (Sites 7, 13, 15, 17, and 19) or no (remaining sites) influence of SRO minerals as evidenced by slightly higher background levels in the x-ray diffractograms in the 26-32° 2-theta range. The modal mineralogy of these horizons consists predominately of kaolin, gibbsite. goethite, and hematite. There are also small amounts of mica or halloysite, quartz, anatase, rutile, magnetite, and ilmenite. The amounts of these minerals vary from site to site, and not all minerals are detected at each site. There is a trend of decreasing kaolin content but increasing gibbsite content with inceasing elevation (and rainfall).

The B horizons above the discontinuity generally can be distinguished from the underlying Bt horizons developed in Koolau basaltic residuum by their lower magnetite and ilmenite contents.

This difference in the contents of resistant minerals is more pronounced in some profiles than in others. The greatest differences are found in the soils of the Paaloa series. These differences were quantified by the determination of the Voigt area for magnetite and ilmenite peaks for three horizons at Sites 9, 13, and 19.

At Site 9, the Ap2, Bt2, and 2Bt4 horizons were analyzed. The values for magnetite (m) and ilmenite (i) for the three horizons at Site 9 are: Ap2, 13 (m) and 29 (i); Bt2, 2 (m) and 6 (i); and 2Bt4, 5 (m) and 21 (i). Thus, the Bt2 horizon, which is suspected to have formed in volcanic ash, has about 1/6 the magnetite of the Ap2 horizon, and about 1/2 as much as in the 2Bt4 horizon. In terms of ilmenite content, the Bt2 horizon has about 1/5 as much as the Ap2, and 1/4 that of the 2Bt4.

At Site 13, the Ab, 2Bw1, and 4Bw3 horizons were analyzed. The values for magnetite (m) and ilmenite (i) for the three horizons at Site 13 are: Ab, 6 (m) and 71 (i); 2Bw1, nondetectable amounts of both minerals; and 4Bw3, 11 (m) and 17 (i). The nondetectable amounts of magnetite and ilmenite in the 2Bw1 horizon are comparable to the 2Bw3 horizon at Site 2 which developed in volcanic ash.

At Site 19, the A2, 2Bt2, and 3BCt horizons were analyzed. The values for magnetite (m) and ilmenite (i) for the three horizons at Site 19 are: A2, 10 (m) and 105 (i); 2Bt2, 3 (m) and 6 (i); and 3BCt, 11 (m) and 27 (i). The 2Bt2 horizon, which is suspected to have formed in volcanic ash, has about 1/3 the magnetite of the A2 horizon, and about 1/4 as much as in the 2Bt4 horizon. In terms of ilmenite content, the 2Bt2 horizon has about 1/18 as much as the A2, and 1/5 that of the 3BCt.

At Sites 2, 9, 13, and 19, the amounts of magnetite and ilmenite are comparable for the soil developed in either basaltic residuum or alluvium. The values for both minerals are nearly identical for the horizons above the discontinuity at Sites 9 and 19. Although the samples are probably contaminated with magnetite and ilmenite to some degree, these values are very low. The 2Bw1 horizon at Site 13, which has the most ash-like morphology of any horizon in the Poamoho area, has no detectable magnetite or ilmenite. The correlation, on the basis of very small amounts of magnetite and ilmenite, of these horizons with those devloped in volcanic ash in the Kunia area seems justified.

The difference in contents of resistant minerals between the soils above and below the discontinuity is interpreted to be due to a difference in parent material. If the soil above and below the discontinuity were derived from the same parent material, differences in magnetite and ilmenite contents would not be likely. Relatively high magnetite and ilmenite contents are found in basalt derived alluvium at Site 14, so the sorting out of heavy resistant minerals by fluvial action does not seem to be a plausible explanation for the small amounts of these minerals above the discontinuity elsewhere.

The stratigraphy of the Schofield-Poamoho area establishes the likely eolian origin of the soil above the discontinuity. Given that the soils developed in volcanic ash in the Kunia area are characterized by small amounts of resistant minerals, the conclusion drawn from the resistant minerals of the B horizons above the discontinuity is that they too developed in volcanic ash but have undergone extensive mineral transformation.

The mineralogy of the soils developed in Koolau basaltic residuum, or alluvium at Site 14 and possibly at Site 9, is very similar to that of the soil above the discontinuity. As stated above, magnetite and ilmenite contents are higher in basalt derived soil. Ilmenite was not always detected in other than trace amounts (such as at Sites 7 and 8), or varied with depth (Site 20). The pattern of ilmenite distribution may be a reflection of the quantities originally in different lava flows.

4.5 Physical Properties

Both bulk density and 1.5 MPa water content were determined on samples from twelve sites on the transect. Clay contents were estimated from the 1.5 MPa water content.

All of the soils on the transect, except for Site 16, have a very noticeable discontinuity (see Appendixes A and B). This discontinuity is expressed as a very abrupt, horizontal contact between contrasting horizons. The contrast is expressed in color, texture, bulk density, and/or structure.

Some comments on the micromorphological analysis of the soil at Site 9 are also included in this section. The complete report of the micromorpholgical analysis by Dr. Stoops is presented in Appendix F.

4.5.1 Kunia Area

Of the high SROM soils, only the physical properties of the Kolekole series at Site 2 were measured. Water content at 1.5 MPa is much less in the A horizons than in the underlying 2Bw horizons. Water content at 1.5 MPa in the 3BCt horizons is similar to the A horizons. The very high 1.5 MPa water content (up to 67%) of the 2Bw horizons is a characteristic of soils with large amounts of SRO minerals (Wada, 1985; Warkentin and Maeda, 1980).

Clay content can be estimated by multiplying the 1.5 MPa water content by 3 (Soil Survey Staff, 1987). This method can be used for the A and 2BCt horizons but it is inappropriate for soil high in SRO minerals (2Bw horizons) because it overestimates the clay content.

The bulk density values fall into three distinct groups. The A horizons (tropospheric dust) have intermediate values, the 2Bw horizons have the low values associated with soils derived from volcanic ash (Wada, 1977; Soil Survey Staff, 1987), and the 3BCt horizons (Waianae alluvium) have exceptionally high values.

The bulk density of the alluvium is about twice that of the ash derived 2Bw horizons. In many of the pedons exposed in the drip irrrigation trench system on the two interfluves to the south of Site 2 there is a thin black layer at the contact of ash and alluvium. It is likely that the alluvium is too dense to permit root penetration and the black layer is presumably humus from the decomposition of the roots at the contact (Foote et al., 1972).

As at Site 2, the A horizon at Site 3 has the lowest estimated clay content in the profile. Based on results from relatively unmixed tropospheric dust deposits in the Poamoho area, the low clay content is thought to be inherited from the parent material.

Neither the 1.5 MPa water content nor the bulk density suggest a volcanic ash origin for any horizon at Site 3. The bulk density values in the 2Bt horizons are higher than those of any other horizon in this profile.

4.5.2 Schofield-Poamoho Area

Physical analyses were measured in samples from Sites 9 through 20. Although some samples have estimated clay contents of 100%, no sample has an extremely high 1.5 MPa water content such as found in the high SROM content soils in the Kunia area.

The changes in clay content within profiles are interpreted to be due primarily to layering of parent materials. The A horizons are formed in the tropospheric dust deposit, but those horizons in cultivation are mixed with B horizon subsoil. The B horizons above the discontinuity probably developed in volcanic ash mixed with some clasts of 2Bt material, and the 2Bt and other horizons from below the discontinuity developed in either transported and/or residual basaltic material.

The relatively low clay content of the Ap horizons is probably a feature inherited from the tropospheric dust. This interpretation is indicated by the relatively low clay contents of unplowed A horizons of the Paaloa Series (Sites 19 and 20). Those A horizons have estimated clay contents as low as 64% (Site 20).

In addition, Stoops (1988, personal communication; Appendix F) reported that the Bt horizons of Site 9 show little evidence of clay illuviation in thin section analysis. There is, therefore, no significant translocation of clay from the Ap to Bt horizons which can account for the 30% difference in clay content between these horizons.

The interpretations of Stoops (Appendix F) contrast with field observations of distinct cutans in the Bt horizons at Site 9. Recognition of cutans using a hand lens, however, can be quite uncertain because pressure faces on peds are shiny and can be mistaken for cutans. Identification of illuvial clay can be problematical in LAC soils (see Soil Survey Staff, 1975, p. 25).

In general, there are no significant differences in estimated clay content between the B horizons above and below the discontinuity. Most of these B horizons have clay contents at or near 100%. In some profiles (Sites 9, 11, and 13) there is greater estimated clay in the horizons above the discontinuity.

Horizons with influence of tropospheric dust generally have higher bulk densities than the underlying B horizons. This is probably not simply due to mechanical compaction of the surface horizons. Unplowed horizons of tropospheric dust (see Sites 19 and 20, and Ab horizon at Site 13) also have very high (up to 1.65 Mg/m^3) bulk densities.

The bulk densities of all but one B horizon above the discontinuity range from 1.2 to 1.5 Mg/m^3. The 2Bw1 horizon at Site 13 is exceptionally low at 1.03 Mg/m^3; this horizon also has a very high estimated clay content relative to the soil below the discontinuity.

Although the bulk density values of all these horizons are much greater than the 0.85 Mg/m^3 requirement for andic properties (Soil Survey Staff, 1987), they are generally lower than those of the truncated soils below the discontinuity.

In addition to the measured physical properties, there are other pertinent observations on characteristics observed in the field. The 2Bw1 horizon of Site 13 is correlated with the oxic horizons of adjacent profiles (e.g., the Bw horizons at Site 12) through stratigraphy and mineralogy. The morphology of this horizon, however, was quite different than the adjacent oxic horizons. This transition in morphology occurs within only a few meters. The 2Bw1 horizon has higher value and chroma when dry, has a more masssive structure, has more pores, and the bulk density (1.03 Mg/m^3) is much lower than the modal Wahiawa series oxic horizon. Of all the soils in the Schofield-Poamoho area, the 2Bw1 horizon at Site 13 has the morphology that most nearly resembles the volcanic ash in the Kunia area.

The 2Bt horizon at Site 9 has what appears to be some gravel-sized clasts of 2BCt material, but this soil is so highly weathered that stratification cannot be identified with certainty. Stratification in the 2Bt4 horizon is hinted in the micromorphological analysis by Dr. Stoops (1988, personal communication; Appendix F). Stoops' interpretation of the 2Bt4 horizon is that it seems to be "a partially homogenised material of the same composition as found in the 2BCt" horizon. If the 2Bt4 horizon formed in slopewash sediments, this soil could be the product of several erosional and depositional events.

Further evidence of the polygenetic history of the soil at Site 9 comes from micromorphological analysis provided by Dr. Stoops. He noted that a polygenetic origin of this soil is indicated by "the presence of linings of microcrystalline gibbsite superposed to clay illuviation coatings" in the 2Bt4 horizon. He thought that the "mobilisation and transport of the Al (in ionic form?) took place after the deposition of the clay coatings, and is probably the result of processes taking place in the superposed materials." The superposed materials referred to here are the Bt horizons which Dr. Stoops described as having "weak or undifferentiated b-fabric . . . characteristic both for oxic materials and for well drained soils developed on volcanic ash."

4.6 Chemical Analyses

Chemical measurements made in support of this study included pH in KCl and in water, cation exchange capacity (CEC) by extraction with ammonium acetate at pH 7, ammonium acetate extractable bases, KCl extractable aluminum, organic carbon, phosphate retention, and oxalate extractable silica, iron, and aluminum.

4.6.1 Kunia Area

Two of the rquirements (Soil Survey Staff, 1987) for andic soil properties (i.e., soils derived from volcanic ash) are: (1) acid oxalate extractable aluminum plus 1/2 acid oxalate extractable iron is 2% or more in the <2 mm fraction and (2) the phosphate retention is more than 85 percent.

Oxalate extraction data from Sites 1A and 1B are presented in Appendix E. The data show that all of the Bw horizons (except the Bw1 of Site 1A) have values that are greater than the 2% needed to meet the requirement for andic properties. These horizons also have relatively high amounts of extractable silica. All horizons that have relatively high values for extractable iron, aluminum, and silica also have high SROM contents as determined by x-ray diffraction analysis.

The high SROM content of the Kolekole series at Site 2 is evident by the very high CEC, organic carbon, and phosphate retention in the 2Bw horizons. Wada (1985) noted that high CEC and organic carbon values are common for soils with high SROM content.

Phosphate retention greater than 85% is also one of the requirements for soils with andic properties (Soil Survey Staff, 1987). At Site 2, the 2Bw horizons have 99% phosphate retention. The A2 and 3BCt1 horizons also have high phosphate retention but not high enough to meet the requirement for andic properties. In addition, the bulk densities of the A2 and 3BCt1 horizons are too high to be considered andic. Phosphate retention of the Bw2B horizon at Site 3A is 49%, which is about one half of that measured in the horizons developed in volcanic ash.

Although oxalate extractable iron and aluminum were not determined in the 2Bw horizons at Site 2, the similar mineralogy of this soil to the Kolekole series at Sites 1a and 1b, suggests that these horizons also probably meet the oxalate extractable iron plus aluminum requirement for andic properties. The low bulk densities of these horizons, the high phosphate retention, and the likelihood of high oxalate extractable iron and aluminum, therefore, strongly suggest that the 2Bw horizons are derived from volcanic ash.

4.6.2 Schofield-Poamoho Area

The CEC of most B horizons above the discontinuity is slightly higher than the 16 $cmol_c$/kg clay required for oxic and kandic horizons. The B horizons above the discontinuity generally have CEC values greater than those of the truncated soil below the discontinuity, and some B horizons have higher CEC values than the A horizons.

No horizon in the Schofield-Poamoho area, however, has a CEC approaching that of the Bw horizons of the Kolekole series. Even though these soils may be developed in volcanic ash, their low CEC values reflect their predominant kaolin/sesquioxide mineralogy.

The organic carbon contents of most B horizons above the discontinuity are below 2% at lower elevations, and 3% at higher elevations.

Phosphate retention was measured at 56% for the Bt2 horizon at Site 9 and 85% for the 2Bw1 horizon at Site 13. This test does not indicate andic properties at Site 9, but the 2Bw1 at Site 13 has the minimum value for a soil to be considered andic.

The oxalate extractable (amorphous) iron of several horizons above and below the discontinuity was measured at Sites 9, 11, 15, 19, and 20. Only the buried A horizon and the 2Bw1 horizon above the discontinuity were analyzed at Site 13. The trend in the data from Sites 19 and 20 is that the soil above the discontinuity has about five times more amorphous iron than the soil below the discontinuity, and at Site 9 there is more iron above the discontinuity by an order of magnitude. The trends in the data from Site 11 and 15 are not as clear, but there is basically more extractable iron above the discontinuity. The 2Bw1 horizon at Site 13 has a comparable amount of extractable iron as for the B horizons above the discontinuity at Sites 11 and 15.

4.7 Classification of Soils

The introduction of the kandic horizon into Soil Taxonomy and the changes in the definition of Oxisols have made it necessary to reevaluate the classification of the soils in central Oahu. One objective of this study is to reclassify the soils according to the latest version of Soil Taxonomy (Soil Survey Staff, 1987). The soils at Sites 2, 3, and 9 through 20 have data sets sufficient for classification purposes. A list of the former and present classifications of the soils at these sites is in Appendix G.

The kandic horizon, in essence, has the chemical characteristics of the oxic horizon and physical characteristics of the argillic horizon. The formulation of the kandic horizon was in response to the difficulty in recognizing illuvial clay in low activity clay (LAC) soils and the existence of soils with properties of both oxic and argillic horizons (Buol, 1986).

The kandic horizon requirement for a clay increase with depth is similar to that for the argillic horizon, except that the clay increase has to occur within a vertical distance of 15 cm. Unlike the argillic horizon in which the clay increase has to be due to illuvial clay, the kandic horizon definition does not specify how the clay increase originated. This lack of genetic inference in the kandic horizon definition is a more realistic approach to dealing with vertical clay distribution in LAC soils for two reasons: (1), clayskins are difficult to recognize in LAC soils; and (2), it can be difficult to establish the genesis of highly weathered soils.

To meet the chemical requirements of the kandic horizon, a soil must have, "starting at the point where the clay increase requirements are met, a CEC of $\leq$16 cmol(+) kg^{-1} clay . . . in at least the major part of the horizon." This definition leads to confusion as to where the chemical requirements need to occur. Does the soil have to have a CEC of $\leq$16 cmol(+) kg^{-1} clay starting at the point where the clay increase is met? Or, can a soil have a kandic horizon if it has a CEC of $\leq$16 cmol(+) kg^{-1} clay only in most of the horizon? John Witty (1988, personal communication), the author of the definition, has said that the intent of the definition was the latter interpretation.

This interpretation of the definition affects the classification of the highly weathered soils in the Wahiawa Basin. In general, the B horizons above the discontinuity have CECs greater than 16 cmol(+) kg^{-1} clay, whereas the horizons below the discontinuity have CECs less than 16 cmol(+) kg^{-1} clay. The clay increase in these soils is due to the stratification of parent materials. The tropospheric dust, which has a relatively low clay content, overlies locally derived soil with a higher clay content. Thus, a clay increase sufficient for a kandic horizon starts approximately at the boundary of the A and B horizons. The CEC requirement is met in the truncated soil below the discontinuity. Because the volume of soil below the discontinuity is greater than the volume of soil above the discontinuity, the "major part of the horizon" that has the clay increase meets the chemical requirement of the kandic horizon. According to Witty's intent of the kandic horizon definition, therefore, the kandic horizon starts at the boundary of the A and B horizons.

The soils to which the above discussion pertains would be classified as Oxisols regardless of whether or not a kandic horizon is recognized. The soil below the discontinuity has oxic properties. In the present Oxisol definition, there is no restriction on having an argillic or cambic horizon overlying an oxic horizon. The soil, therefore, would still classify as an Oxisol even if the diagnostic horizon above the discontinuity were considered to be an argillic horizon. The recognition of a kandic horizon mainly becomes important at the Great Group level of taxonomy.

According to Soil Taxonomy, soils were classified as Oxisols if they met one of two sets of conditions. They could have had aquic moisture regimes and plinthite within 30 cm of the soil surface. This set of properties was deleted from the current definition of Oxisols. Soils could also have keyed out as Oxisols if, within 2 m of the soil surface, they had an oxic horizon that did not have an overlying argillic horizon. A large percentage of the soils of central Oahu were classified as Oxisols because of this definition. The soils in central Oahu that were not classified as Oxisols were either Inceptisols or Ultisols.

In the present definition, soils are classified as Oxisols if they meet the requirements of one of two sets of properties. In one set, soils classify as Oxisols if they have an oxic horizon within 150 cm of the soil surface and do not have a clay increase necessary to define a kandic horizon. In the study area, soils that have oxic horizons with gradual clay increases with depth classify as Oxisols under this set of requirements.

In the other set of properties, soils classify as Oxisols if they have more than 40% clay in the surface horizon and have either an oxic or kandic horizon within 150 cm of the surface. In the study area, soils with kandic horizons classify as Oxisols under this set of requirements. Allowing soils with kandic horizons to classify as Oxisols has necessitated the change in classification of the Ultisols of the Wahiawa Basin to Oxisols.

Assumptions were made in classifying some profiles because either data were lacking, certain analyses were not performed, or samples were not collected to a sufficient depth. The transition between ustic and udic moisture regimes is assumed to occur between the Wahiawa and Paaloa series. Citrate dithionite extractable iron, which is used to determine mineralogy classes in Oxisols, was only measured at Sites 9, 11, 13, 15, 19, and 20. The mineralogy of other Oxisols is estimated based on x-ray difraction analysis and the trend in extractable iron at the above sites.

At Sites 10, 11, 13, and 14, most of the solum has CEC values greater than 16 cmol(+) kg^{-1} clay. Oxic CEC requirements are met only at the lower parts of the profiles, but the thickness of the oxic material was less than 30 cm at Sites 10, 11, and 13. It is assumed that enough oxic material occurred below the sampled oxic material to meet the thickness requirements for oxic horizons. It is also assumed that after reaching a minimum, the CEC increased in deeper horizons (such as at Sites 18 and 19) and the major portion of the profile does not have oxic CEC values. The soils at Sites 10, 11, 13, and 14 are, therefore, considered to have oxic horizons instead of kandic horizons and are classified as Haplo- Great Groups.

Because a lithologic discontinuity (volcanic ash over alluvium) exists in the Kolekole series, the argillic horizon requirement for a clay increase is waived (Soil Survey Staff, 1987). In this situation, there only needs to be a recognition of illuvial clay in the buried and/or truncated soil to be an argillic horizon. The prominent red cutans in the alluvium of the Kolekole series clearly meet this criterion.

Foote et al. (1972) classified the Kolekole series as an Ustoxic Humitropepts. In this study, the Kolekole series is classified as an Ultisol because of the occurrence of an argillic horizon.

The principal differences between the classification of soils by Foote et al. (1972) and this study are shown in Appendix G.

5. SUMMARY AND CONCLUSIONS

Research conducted several decades ago established that the surface horizons of Hawaii soils were influenced by the addition of tropospheric dust. The results of the present study suggest that, in addition to quartz and mica, the tropospheric dust is composed of a suite of minerals including magnetite, maghemite, ilmenite, anatase, rutile, and pseudobrookite. This assertion is based on the association of the above minerals with quartz-bearing deposits that are relatively unmixed with locally derived subsoil. The results of this study also indicate that the difference in quartz contents between the Paaloa and Wahiawa series is a gradual transition, not the abrupt decrease reported by Jackson et al. (1971).

This study has established that discontinuities within soil profiles in the Wahiawa Basin are not isolated features that occur mainly on the edges of interfluves. On the contrary, most soils in the study area have a discontinuity. The discontinuity occurs in soils of all taxonomic units in the study area.

Soil profiles were observed in extensive trenches on an interfluve north of Poamoho Stream. An erosion surface, or discontinuity, in these profiles is an uninterrupted feature that traverses the length of the interfluve and all geomorphic surfaces. The discontinuity can also be traced from the highest geomorphic surface on that interfluve to the bottom of the adjacent fossil stream channel. Except in the fossil stream channel, the B horizons above the discontinuity on this interfluve appear to be a single stratigraphic layer that mantles all geomorphic surfaces. The implications of this are that all geomorphic surfaces on this interfluve were in existence at the same time, and all soils above the erosion surface are the same age and younger than the erosion surface. The age of the B horizons is post-erosional because the layer in which they developed mantles the fossil stream channel.

The lack of alluvial material above the discontinuity in the fossil channel indicates that Poamoho Stream had captured the unnamed tributary that used to flow there and had isolated the interfluve prior to the deposition of the soil material on the erosion surface. If this were the case, the soil above the erosion surface is an eolian deposit because there would have been no upslope sediment source once the interfluve was isolated.

Other evidence of an eolian origin of the soil above the discontinuity is found at two sites near the center of the Wahiawa Basin. These sites are located on knolls and both have about a meter of soil above a discontinuity. An eolian origin for the soil above the discontinuity is indicated because there is no uphill sediment source.

There are, therefore, two eolian components in the soils of the Wahiawa Basin. The tropospheric dust is the parent material for the A horizons. The other eolian component formed the parent material for the B horizons above the erosion surface. Although it is no longer recognizeable as such because of the physical and chemical transformations that it has undergone, this other component was most likely volcanic ash.

Mineralogical analysis supports the interpretation that the soil above the discontinuity is derived from a different parent material than the soil below the discontinuity. In the B horizons above the discontinuity, magnetite and ilmenite, two resistant primary minerals, generally occur in very low amounts relative to soil developed in either basaltic residuum or alluvium. If the soil above the discontinuity were slopewash derived from the underlying soil developed in basalt residuum, then it should have amounts of magnetite and ilmenite that are comparable to the underlying soil.

Both magnetite and ilmenite occur in only trace amounts in volcanic ash in the Kolekole series. Petrographic analysis (Winchell, 1947) of tuff samples indicated that pyroclastics of the Honolulu Volcanics have very low amounts of magnetite and ilmenite relative to basalt. The very low amounts of magnetite and ilmenite in the B horizons above the discontinuity suggest that the parent material of the soils examined in this study was volcanic ash.

The conclusion of this study is that the highly weathered B horizons of the Oxisols in the Wahiawa Basin developed in volcanic ash. This conclusion is based on the two independent lines of evidence given above: the stratigraphy indicates an eolian origin for the soil above the discontinuity and the mineralogy indicates that the highly weathered B horizons developed in a parent material that had low amounts of magnetite and ilmenite. Volcanic ash on Oahu is an eolian material that has very low amounts of both magnetite and ilmenite.

Neither line of evidence alone provides conclusive proof of a pyroclastic origin for the B horizons above the discontinuity. When taken together, however, these lines of evidence strongly support the interpretation that truncated soils developed in basaltic residuum and alluvium in the Wahiawa Basin were mantled with volcanic ash. This interpretation is in agreement with the general geologic history of Oahu: cessation of lava discharge from Koolau Volcano was followed by erosion and subsequent production of pyroclastic deposits.

Little is known about the pyroclastic deposits of the Kolekole Volcanics, but the Honolulu Volcanics produced at least forty eruptions which range in age from 800,000 years to 30,000 years (Macdonald et al., 1983). It seems likely that one or more of the eruptions of the Honolulu and Kolekole Volcanics could have produced pyroclastics which mantled the Wahiawa Basin.

The soils in central Oahu provide a record of alternating periods of landscape stability and instability. This record is the basis for constructing the following sequence of events for the landscape evolution of central Oahu: (1) erosion of Koolau and Waianae Volcanos; (2) formation of soils in residual basalt; (3) formation of alluvial fans (and burial of red soils) at the base of the Waianae Range; (4) development of soils in the Waianae alluvial fans; (5) basin-wide truncation of soil profiles and concurrent downcutting of stream channels; (6) deposition of one or more volcanic ash layers possibly separated by erosional periods; (7) formation of soils in the volcanic ash and the concurrent accumulation of tropospheric dust from mainland Asia; and (8) further downcutting of stream channels but stabilization of interfluve surfaces as evidenced by the accumulation of tropospheric dust.

Appendix A. Photographs of soil profiles.

Figure 7. Kolekole series at Site 1B. Discontinuity at about 90 cm.

Figure 8. Kolekole series at Site 2. Discontinuity at 118 cm.

Figure 9. Wahiawa series at Site 3. Discontinuity at 108 cm.

Figure 10. Kunia series at Site 4. Thin lenses of SROM soil between slabs of Old Waianae alluvium. Knife blade rests on contact with alluvium at depth of about 70 cm.

Figure 11. Soil at Site 5 developed in volcanic ash with many clasts of old Waianae alluvium in a delineation of Helemano series map unit.

Figure 12. Wahiawa series at Site 6. Discontinuity behind shovel handle. Depth to discontinuity is about 1.5 meters.

Figure 13. Manana series at Site 7. Knife blade is about 10 cm above discontinuity which is at a depth of about 70 cm.

Figure 14. Soil mapped as Kolekole series at Site 8. Knife blade at discontinuity which is at a depth of about 1 meter.

Figure 15. Manana series at Site 9. Discontinuity at depth of about 70 cm.

Figure 16. Manana series at Site 9. Discontinuity at 70 cm.

Figure 17. Wahiawa series at Site 10. Tip of knife blade at depth of about 25 cm. Discontinuity at 60 cm.

Figure 18. Wahiawa series at Site 11. Tip of knife blade at depth of about 30 cm. Discontinuity at depth of about 85 cm.

Figure 19. Wahiawa series at Site 12. Tip of knife blade at depth of about 20 cm. Discontinuity at a depth of about 95 cm.

Figure 20. Wahiawa series at Site 13. Tip of knife blade at a depth of about 30 cm. Contact between 3Bw2 and 4Bw3 horizons is about 10 cm above floor of the trench.

Figure 21. Wahiawa series at Site 14. Tip of knife blade is at contact between Bw3 and 2Bt1 horizons.

Figure 22. Wahiawa series at Site 15. Discontinuity at depth of about 115 cm.

Figure 23. Wahiawa series at Site 16. No abrupt discontinuity was observed in this profile in the field.

Figure 24. Paaloa series at Site 17. Discontinuity at 62 cm.

Figure 25. Paaloa series at Site 18. Discontinuity has a wavy boundary between 40-45 cm.

Figure 26. Paaloa series at Site 19. Discontinuity at a depth between 68-73 cm.

Figure 27. Paaloa series at Site 20. Discontinuity at a depth between 35-40 cm.

Appendix B - Soil Profile Descriptions

Site 1A - Kolekole series

The soil at Site 1A was sampled from a drip irrigation trench on the interfluve adjacent to and south of Kunia Camp. This site occurs at an elevation of about 960 feet on an alluvial fan which was mantled with volcanic ash.

Ap - 0 to 35 cm; dark reddish brown (5YR3/3) silty clay loam, yellowish red (5YR 4/6) when dry; strong granular structure; many, very fine and fine roots; abrupt, wavy boundary.

Bw1 - 35 to 60 cm; dark red (10R 3/6) silty clay loam, red (10R 4/8) when dry; massive parting to fine and medium subangular blocky structure; few, very fine and fine roots; clear, wavy boundary.

Bw2 - 60 to 90 cm; red (2.5YR 4/6) silt loam, yellowish red (5YR 4/8) when dry; massive parting to fine and medium subangular blocky structure; common, very fine and fine roots; slightly smeary; clear, wavy boundary.

Bw3 - 90 to 105 cm; red (2.5YR 4/6) silt loam, yellowish red (5YR 4/8) when dry; massive parting to fine and medium subangular blocky structure; few, very fine roots; smeary; very abrupt, smooth boundary.

2BCt1 - 105 to 130 cm; dark reddish brown (5YR 3/2) silty clay loam, dark reddish brown (5YR 3/3) when dry; massive parting to fine and medium angular blocky structure; common, prominent dark red (2.5 YR 3/6) cutans; very few, very fine roots; very abrupt, smooth boundary.

Bw4 - 130 to 145 cm; dark reddish brown (5YR 3/4) silt loam, strong brown (7.5YR 5/6) when dry; massive parting to fine and medium subangular blocky structure; few, very fine and fine roots; smeary; very abrupt, smooth boundary.

2BCt2 - 145 to 175+ cm; dark reddish brown (5YR 3/2) silty clay loam, reddish brown (5YR 3/4) when dry; massive parting to fine and medium angular blocky structure; common, prominent dark red (2.5YR 3/6) cutans, red (2.5YR 4/6) when dry; no roots.

Site 2 - Kolekole series

Site 2 was sampled from a profile exposed in the gulch that is adjacent to and north of Kunia Camp. This site is approximately 450 meters west (upslope) of Kunia Road. The elevation is about 860 feet.

Ap1 - 0 to 25 cm; dark reddish brown (2.5YR 3/4) silty clay loam, dark red (2.5YR 3/6) when dry; strong granular structure; slightly hard, friable, slightly sticky, and slightly plastic; many, very fine and fine roots; not effervescent with hyrdrogen peroxide; clear, wavy boundary.

Ap2 - 25 to 60 cm; dark reddish brown (2.5YR 2.5/4) silty clay loam, dark reddish brown (2.5YR 3/4) when dry; strong, fine and medium, subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; many, very fine and fine roots; not effervescent with hyrdrogen peroxide; abrupt, wavy boundary.

2Bw1 - 60 to 85 cm; dark red (2.5YR 3/6) silt loam, yellowish red (5YR 5/8) when dry; massive parting to moderate, fine and medium subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; common, very fine and fine roots; common fine pores; not effervescent with hyrdrogen peroxide; about 5% clasts of 2BCt material; slightly smeary; clear, wavy boundary.

2Bw2 - 85 to 100 cm; dark red (2.5YR 3/6) silt loam, yellowish red (5YR 5/8) when dry; massive parting to moderate, fine and medium subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; few, very fine roots; common fine pores; not effervescent with hyrdrogen peroxide; about 10% clasts of 2BCt material; smeary; clear, wavy boundary.

2Bw3 - 100 to 118 cm; red (2.5YR 4/6) silt loam, yellowish red (5YR 5/6) when dry; massive parting to moderate, fine and medium angular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; very few, very fine roots; common fine pores; not effervescent with hyrdrogen peroxide; about 15% clasts of 2BCt material; smeary; very abrupt, smooth boundary.

3BCt1 - 118 to 138 cm; dark reddish brown (5YR 3/3) clay loam, dark reddish brown (5YR 3/4) when dry; massive parting to strong, fine and medium subangular blocky structure; hard, firm, slightly sticky, and plastic; brittle when dry; no roots; very few fine pores; common, prominent red (2.5YR 4/8) and dark red (10R 3/6) cutans on ped faces and pores; not effervescent with hyrdrogen peroxide; clear, wavy boundary.

3BCt2 - 138 to 160 cm; dark reddish brown (5YR 3/3) clay loam, dark reddish brown (5YR 3/4) when dry; massive parting to strong, fine and medium subangular blocky structure; hard, firm, slightly sticky, and plastic; brittle when dry; no roots; very few fine pores; few, prominent red (2.5YR 4/8) and dark red (10R 3/6) cutans on ped faces and pores; not effervescent with hyrdrogen peroxide; about 10% sand and gravel; clear, wavy boundary.

3BCt3 - 160 to 190+ cm; dark reddish brown (5YR 3/3) sandy clay loam, dark reddish brown (5YR 3/4) when dry; massive parting to strong, fine and medium subangular blocky structure; hard, firm, slightly sticky, and plastic; brittle when dry; no roots; very few fine pores; few, prominent red (2.5YR 4/8) and dark red (10R 3/6) cutans on ped faces and pores; not effervescent with hyrdrogen peroxide; about 30% sand and gravel.

Site 3A - Wahiawa series

Site 3A is located on the interfluve adjacent to and north of Kunia Camp. The soil was sampled from the roadcut along Kunia Road at an elevation of about 840 feet. Site 3A is about 450 meters east (downslope) of Site 2 and it is on the same geomorphic surface.

Ap - 0 to 20 cm, dark reddish brown (2.5YR 2.5/4) silty clay loam dark reddish brown (2.5YR 3/4) when dry; strong, very fine, granular structure; slightly hard, friable, slightly sticky, and slightly plastic; many very fine and fine roots; few fine pores; no effervescence with hydrogen peroxide; clear, smooth boundary.

Bw1 - 20 to 30 cm, dark reddish brown (2.5YR 3/4) silty clay loam, dark red (2.5YR 3/6) when dry; strong, very fine, subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; common very fine and fine roots; common fine pores; no effervescence with hydrogen peroxide; clear, smooth boundary.

Bw2 - 30 to 108 cm, dark reddish brown (2.5YR 3/4) silty clay loam, dark red (2.5YR 3/6) when dry; strong, very fine, subangular blocky structure; hard, firm, very sticky, and plastic; common very fine and fine roots; common fine pores; 5-10% rounded clasts from 2Bt; very slight effervescence with hydrogen peroxide; very abrupt, smooth boundary.

2Bt - 108 to 150+ cm, dark red (2.5YR 3/2) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to strong, very fine, subangular blocky structure; hard, firm, sticky, and plastic; few very fine roots; few, distinct red (10R 4/8) cutans on ped faces; common pressure faces; no effervescence with hydrogen peroxide.

SITE 9 - Manana series

Site 9 is located on the north side of the interfluve just south of the fossil channel described in Section 4.2.2. This soil is exposed in a roadcut along Kamehameha Highway at an elevation of 950 feet.

Ap1 - 0 to 12 cm, dark reddish brown (2.5YR 3/4) silty clay loam dark red (2.5YR 3/6) when dry; strong, very fine, granular structure; slightly hard, friable, slightly sticky, and slightly plastic; many very fine and fine roots; few fine pores; slight effervescence with hydrogen peroxide; clear, smooth boundary.

Ap2 - 12 to 30 cm, dark reddish brown (2.5YR 3/4) silty clay loam, reddish brown (5YR 4/4) when dry; strong, coarse, subangular blocky parting to strong, very fine, subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; common very fine and fine roots; few fine pores; slight effervescence with hydrogen peroxide; abrupt, smooth boundary.

Bt1 - 30 to 47 cm, dark red (10R 3/6) silty clay loam, red (10R 4/8) when dry; strong, coarse, subangular blocky parting to strong, very fine, subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; common very fine and fine roots; common fine pores; very few, faint cutans on some peds; no effervescence with hydrogen peroxide; clear, smooth boundary.

Bt2 - 47 to 82 cm, dark red (10R 3/6) clay, red (10R 4/8) when dry; strong, coarse, subangular blocky parting to strong, very fine, subangular blocky structure; hard, firm, very sticky, and plastic; common very fine and fine roots; common fine pores; few (ca. 25%), distinct cutans on all peds; few (ca. 10%) pressure faces; 5% clasts from 2Bt; no effervescence with hydrogen peroxide; clear, wavy boundary.

Bt3 - 82 to 91 cm, dark red (10R 3/6) clay, red (10R 4/8) when dry; strong, very fine, subangular blocky structure; hard, firm, very sticky, and plastic; few very fine and fine roots; common fine pores; common (ca. 45%), distinct and prominent cutans on all peds; few (ca. 10%) pressure faces; 15% clasts from 2Bt; no effervescence with hydrogen peroxide; very abrupt, smooth boundary.

2Bt4 - 91 to 150 cm, dark red (10R 3/6) clay, red (10R 4/6) when dry; strong, very fine, subangular blocky structure; hard, firm, very sticky, and plastic; few very fine roots; common fine pores; many (ca. 70%), distinct and prominent cutans on all peds; few (ca. 10%) pressure faces; few shiny black and white specks; no effervescence with hydrogen peroxide; diffuse, wavy, boundary.

2BCt - 150 to 200+ cm, dark reddish brown (2.5YR 3/4) clay, dark red (2.5YR 3/6) when dry; strong, very fine, subangular blocky structure; hard, firm, very sticky, and plastic; few very fine roots; common fine pores; many (ca. 70%), distinct and prominent cutans on all peds; few (ca. 10%) pressure faces; few shiny black and white specks; 5-10% saprolite fragments; no effervescence with hydrogen peroxide.

SITE 10 - Wahiawa series

This site occurs at approximately 1015 feet elevation on the interfluve adjacent to and south of the fossil channel. Its geomorphic position is the summit/shoulder of the scarp that separated the two lowest geomorphic surfaces on this interfluve.

Ap - 0 to 28 cm, dark reddish brown (2.5YR 2.5/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive; hard, firm, very sticky, and plastic; common fine roots; slight effervescence with hydrogen peroxide; abrupt, smooth boundary.

Bw1 - 28 to 56 cm, dusky red (10R 3/4) clay, red (10R 4/8) when dry; massive parting to moderate, fine, subangular blocky structure; hard, firm, sticky, and plastic; few fine roots; few fine pores; very few, distinct pressure faces; very slight effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw2 - 56 to 60 cm, dark red (10R 3/6) silty clay, dark red (10R 3/6) when dry; massive; hard, friable, slightly sticky, and slightly plastic; few very fine roots; common fine pores; no effervescence with hydrogen peroxide; very abrupt, wavy boundary.

2Bw3 - 60 to 75 cm, dusky red (10R 3/4) clay, dusky red (10R 3/4) when dry; massive parting to strong, fine, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; few fine pores; common, prominent pressure faces; few N 2.5/0 stains on ped faces and root channels; very slight effervescence with hydrogen peroxide; clear, wavy boundary.

2Bw4 - 75 to 88 cm, dark reddish brown (2.5YR 3/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to strong, fine, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; few fine pores; common, distinct pressure faces; very slight effervescence with hydrogen peroxide; clear, wavy boundary.

2Bw5 - 88 to 105+ cm, dark reddish brown (2.5YR 3/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to strong, fine to medium, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; few fine pores; many distinct pressure faces; no effervescence with hydrogen peroxide.

SITE 11 - Wahiawa series

Site 11 is located on the highest geomorphic surface on the interfluve adjacent to and south of the fossil channel. This site is at an elevation of approximately 1085 feet.

Ap1 - 0 to 30 cm, dusky red (10R 3/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to moderate, very fine granular structure; hard, firm, very sticky, and plastic; common very fine and fine roots; very few (<1%), faint, pressure faces; violent effervescence with hydrogen peroxide; clear, wavy boundary.

Ap2 - 30 to 43 cm, dusky red (10R 3/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to moderate, very fine granular structure; hard, firm, very sticky, and plastic; few very fine roots; very few (<1%), faint, pressure faces; strong effervescence with hydrogen peroxide; clear, wavy boundary.

Bw - 43 to 53 cm, dark red (10R 3/6) clay, red (10R 4/8) when dry; massive parting to moderate, very fine granular and very fine and fine, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; very few (ca. 5%), faint, pressure faces; few, fine and medium pores; very few (ca. 1%) fine N 3/0 (very dark gray) stains in pores; very slight effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bt1 - 53 to 84 cm, dark red (10R 3/6) clay, red (10R 4/6) when dry; moderate, very fine to medium, angular blocky structure; hard, firm, very sticky, and plastic; no roots; few, distinct, pressure faces; few (<10%), distinct cutans; common, very fine and fine pores; very few, fine N 3/0 (very dark gray) stains on ped faces; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

Bt2 - 84 to 87 cm, dark red (10R 3/6) clay, red (10R 4/7) when dry; massive parting to weak, very fine and fine, angular blocky structure; hard, firm, very sticky, and plastic; no roots; few distinct, pressure faces; few, faint cutans; common, very fine and fine pores; very few (ca. 1%), fine N 3/0 (very dark gray) stains on ped faces and pores; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

2Bt3 - 87 to 103 cm, red (10R 4/6) clay, red (10R 4/8) when dry; massive parting to moderate, fine and medium, angular blocky structure along planes of weakness due to pervasive slickensides; hard, firm, very sticky, and plastic; no roots; common, distinct, pressure faces; common, faint, dark red (10R 3/6) cutans on ped faces; common, very fine and fine pores; very few (<1%), fine N 3/0 (very dark gray) stains in pores; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

2Bt4 - 103 to 127+ cm, red (10R 4/6) clay, red (10R 4/8) when dry; massive parting to moderate, fine and medium, angular blocky structure along planes of weakness due to pervasive slickensides; hard, firm, very sticky, and plastic; no roots; common, distinct, pressure faces; many, distinct, dark red (10R 3/6) cutans on ped faces; very few, faint, red (10R 4/6) stains in pores; common, very fine and fine pores; very few (<1%), fine N 3/0 (very dark gray) stains in pores; very slight effervescence with hydrogen peroxide; few boulders.

SITE 12 - Wahiawa series

Site 12 is at an elevation of approximately 1060 feet on the interfluve adjacent to and south of the fossil channel. This site is on one of the minor surfaces between the highest geomorphic surface (Site 11) and the fossil channel.

Ap1 - 0 to 19 cm, dark reddish brown (2.5YR 2.5/4) silty clay, dark reddish brown (2.5YR 3/4) when dry; strong, very fine granular and fine subangular blocky structure; hard, friable, sticky, and slightly plastic; common very fine and fine roots; violent effervescence with hydrogen peroxide; clear, smooth boundary.

Ap2 - 19 to 38 cm, dark reddish brown (2.5YR 2.5/4) silty clay, dark red (2.5YR 3/6) when dry; massive and strong, very fine and fine granular structure; hard, friable, sticky, and slightly plastic; few very fine and fine roots; few (ca. 1%), faint, pressure faces; violent effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw1 - 38 to 47 cm, dusky red (10R 3/4) clay, dark red (10R 3/6) when dry; massive; hard, firm, very sticky, and plastic; few very fine roots; very few (ca. 5%), faint, pressure faces; few (ca. 1%) fine pores; very few (ca. 1%) fine N 3/0 (very dark gray) stains on ped faces and pores; strong effervescence with hydrogen peroxide; discontinuous horizontal slickenside layer separates this horizon from Bw2; clear, wavy boundary.

Bw2 - 47 to 74 cm, dark reddish brown (2.5YR 3/4) silty clay, dark red (2.5YR 3/6) when dry; weak, coarse prismatic and weak, fine and medium, subangular blocky structure; hard, firm, sticky, and plastic; no roots; common, distinct pressure faces; few, very fine and fine pores; few (ca. 5%) fine N 3/0 (very dark gray) stains on ped faces and pores; slight effervescence with hydrogen peroxide; diffuse, wavy boundary.

Bw3 - 74 to 95 cm, dark reddish brown (2.5YR 3/4) silty clay, dark red (2.5YR 3.5/6) when dry; weak, fine subangular blocky structure; hard, firm, sticky, and plastic; no roots; few faint pressure faces; few, very fine, fine, and medium pores; very few (ca. 1%) fine N 3/0 (very dark gray) stains on ped faces and pores; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

2Bt - 95 to 120+ cm, dark reddish brown (2.5YR 3/4) silty clay loam, dark reddish brown (2.5YR 3/4) when dry; massive; hard, friable, slightly sticky, and slightly plastic; no roots; few (ca. 25%), prominent pressure faces; nearly continuous, distinct, dark red (10R 3/6-8), cutans and soil material in pores; few (ca. 20%) dark red (10R 3/6) cutans on ped faces; few, very fine and fine pores; very few (ca. 1%) fine N 3/0 (very dark gray) stains on ped faces and pores; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

SITE 13 - Wahiawa series

Site 13 is located on the mid-level geomorphic surface of the interfluve adjacent to and sorth of the fossil channel. It is at an elevation of about 1040 feet, on the surface adjacent to the hillsope leading into the fossil channel. The erosion surface that forms the boundary between the 3Bw2 and 4Bw3 horizons is the same one that separates the Bw3 and 2Bt horizons at Site 12.

Ap1 - 0 to 20 cm, dark reddish brown (2.5YR 2.5/4) clay, dark reddish brown (2.5YR 3/4) when dry; massive and some moderate, thick to very thick, platy structure; hard, firm, sticky, and slightly plastic; very few, fine roots; few faint cutans; violent effervescence with hydrogen peroxide; abrupt, smooth boundary.

Ap2 - 20 to 40 cm, dark reddish brown (5YR 3/3) clay, dark reddish brown (10R 4/8) when dry; massive parting to moderate, fine to coarse, subangular blocky structure; hard, firm, sticky, and slightly plastic; very few, fine roots; few, faint pressure faces and cutans; slight effervescence with hydrogen peroxide; abrupt, smooth boundary.

Ab - 40 to 55 cm, dark brown (10YR 3/3) silty clay, brown (10YR 3.5/3) when dry; massive parting to moderate, fine to coarse, subangular blocky structure; hard, firm, sticky, and plastic; very few, very fine roots; few fine pores; very few, faint pressure faces and cutans; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

2Bw1 - 55 to 83 cm, dark red (2.5YR 3/6) silty clay, red (2.5YR 4/6) when dry; massive parting to moderate, fine to coarse, subangular blocky structure; slightly hard, friable, sticky, and plastic; no roots; common to many fine and very fine pores; very few, faint pressure faces; very few N 3/0 (very dark gray) stains on ped faces; no effervescence with hydrogen peroxide; abrupt, wavy boundary.

3Bw2 - 83 to 96 cm, yellowish red (5YR 4/6) gravelly loam, yellowish red (5YR 5/8) when dry; strong, very fine to medium, subangular blocky structure; hard, friable, slightly sticky, and slightly plastic; no roots; few to many very fine and fine pores; 40% gravel; stratified alluvium composed of 4Bw3 material; very slight effervescence with hydrogen peroxide; very abrupt, wavy boundary.

4Bw3 - 96 to 116+ cm, dark reddish brown (2.5YR 3/4) loam, dark red (2.5YR 3/6) when dry; massive parting to moderate, very fine to coarse, subangular blocky structure; hard, friable, slightly sticky, and slightly plastic; no roots; few very fine and fine pores; few distinct pressure faces and faint cutans; nearly continuous N 3/0 (very dark gray) stains at top of horizon; very slight effervescence with hydrogen peroxide.

SITE 14 - Wahiawa series

Site 14 is located at the bottom of the fossil stream channel. It is at an elevation of about 1020 feet. This profile has two discontinuities. The discontinuity that forms the contact between the 2Bt2 and 3Bt3 horizons is the same one that sepatates the 3Bw2 and 4Bw3 horizons at Site 13.

Ap1 - 0 to 15 cm, dark reddish brown (5YR 3/3) clay, reddish brown (5YR 4/4) when dry; massive parting to moderate, fine, granular structure; hard, firm, sticky, and plastic; few, medium and common very fine and fine roots; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

Ap2 - 15 to 30 cm, dark reddish brown (5YR 3/3) clay, reddish brown (5YR 4/3) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and plastic; few, fine roots; few, very fine pores; no effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw1 - 30 to 50 cm, dark red (2.5YR 3/6) clay, dark red (2.5YR 3/6) when dry; moderate, fine, subangular blocky structure; hard, firm, very sticky, and plastic; few very fine roots; very few, faint, pressure faces; common, very fine pores; very few, fine N 3/0 (very dark gray) stains on ped faces and pores; no effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw2 - 50 to 66 cm, dark reddish brown (2.5YR 3/5) clay, reddish brown (2.5YR 4/5) when dry; moderate, fine angular blocky structure; hard, firm, very sticky, and plastic; few very fine roots; few (ca. 20%), distinct pressure faces; common, very fine pores; few, fine, very dark gray (N 3/0) stains on ped faces and pores; strong effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw3 - 66 to 72 cm, dark red (2.5YR 3/6) clay, red (2.5YR 4/6) when dry; moderate, very fine angular blocky structure; hard, firm, very sticky, and plastic; few very fine roots; very few (ca. 5%), faint, pressure faces; many, very fine pores; slight effervescence with hydrogen peroxide; discontinuous horizon, 0 to 7 cm thick; very abrupt, wavy boundary.

2Bt1 - 72 to 92 cm, dark reddish brown (2.5YR 3/5) clay, reddish brown (2.5YR 4/5) when dry; massive parting to moderate, very fine angular blocky structure; hard, firm, very sticky, and plastic; no roots; common (ca. 40%), distinct pressure faces; very few, faint cutans; few, very fine pores; strong effervescence with hydrogen peroxide; few, fine, very dark gray (N 3/0) stains on ped faces and pores; ca. 5% rounded, non-stratified gravel in lower 10 cm of horizon; abrupt, wavy boundary.

2Bt2 - 92 to 95 cm, dark red (2.5YR 3/6) clay, red (2.5YR 4/6) when dry; massive parting to moderate, very fine subangular blocky structure; hard, firm, very sticky, and plastic; no roots; very few (ca. 2%), faint, pressure faces; very few, faint cutans; common, very fine and fine pores; strong effervescence with hydrogen peroxide; ca. 5% rounded, non-stratified gravel; very abrupt, wavy boundary.

3Bt3 - 95 to 105 cm, dark reddish brown (5YR 3/5) clay, reddish brown (5YR 4/3) when dry; massive; hard, firm, very sticky, and plastic; no roots; few, distinct pressure faces; few, prominent cutans; few, very fine and fine pores; no effervescence with hydrogen peroxide; ca. 35% rounded, stratified gravel; abrupt, wavy boundary.

3Bt4 - 105 to 140 cm, dark reddish brown (5YR 3/5) clay, reddish brown (5YR 4/3) when dry; massive; hard, firm, very sticky, and plastic; no roots; few, distinct pressure faces; few, prominent cutans; few, very fine and fine pores; no effervescence with hydrogen peroxide; no gravel; abrupt, wavy boundary.

3Bt5 - 140 to 148+ cm, dark reddish brown (5YR 3/5) clay, reddish brown (5YR 4/3) when dry; massive; hard, firm, very sticky, and plastic; no roots; few, distinct pressure faces; few, prominent cutans; few, very fine and fine pores; no effervescence with hydrogen peroxide; 10 to 15% rounded, stratified gravel and cobbles; abrupt, wavy boundary.

SITE 15 - Wahiawa series

Site 15 is located on the interfluve between Poamoho Stream and its unnamed tributary to the north. It is on the lowest of the geomorphic surfaces on this interfluve, at an elevation of about 1150 feet.

Ap1 - 0 to 30 cm, dusky red (2.5YR 3/2) silty clay, dark reddish brown (2.5YR 3/4) when dry; strong, very fine granular and fine and medium, subangular blocky structure; hard, friable, sticky, and slightly plastic; common, very fine and fine roots; very few (<1%), faint, pressure faces; slight effervescence with hydrogen peroxide; clear, wavy boundary.

Ap2 - 30 to 41 cm, dark reddish brown (2.5YR 2.5/4) clay, dark reddish brown (2.5YR 3/4) when dry; strong, medium and coarse, subangular blocky structure; hard, firm, very sticky, and plastic; common, very fine and fine roots; very few, faint, pressure faces; few, very fine pores; very slight effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw1 - 41 to 56 cm, dusky red (10R 3/4) clay, red (10R 4/6) when dry; strong, fine to coarse, subangular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; very few, faint, pressure faces and cutans; common, very fine and fine pores; very slight effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw2 - 56 to 110 cm, dusky red (10R 3/4) clay, red (10R 4/6) when dry; strong, fine to coarse, subangular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; common, distinct, pressure faces; few, distinct cutans; common, very fine and fine pores; few, fine, black (N 3/0) stains on ped faces; very slight effervescence with hydrogen peroxide; very abrupt, smooth boundary.

Bw3 - 110 to 113 cm, dark red (10R 3/6) clay, red (10R 4/8) when dry; moderate, very fine and fine, subangular blocky structure; hard, friable, sticky, and slightly plastic; few, very fine and fine roots; very few, faint pressure faces; common, very fine and fine pores; few, fine, black (N 2/0) stains on ped faces and pores; slight effervescence with hydrogen peroxide; very abrupt, smooth boundary.

2Bt1 - 113 to 125 cm, dusky red (10R 3/4) clay, dark red (2.5YR 3/6) when dry; strong, medium, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; common (ca. 25%), distinct pressure faces; common, distinct and prominent cutans on ped faces; few, very fine pores; ca. 3% saprolite fragments; no effervescence with hydrogen peroxide; clear, wavy boundary.

2Bt2 - 125 to 165 cm, dusky red (10R 3/4) clay, dusky red (10R 3/4) when dry; strong, fine and medium, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; common (ca. 25%), distinct pressure faces; common (ca. 35%), distinct and prominent cutans on ped faces; few, very fine pores; ca. 3% saprolite fragments; few, round, black (N 2/0) concretions; very slight effervescence with hydrogen peroxide; clear, wavy boundary.

2Bt3 - 165 to 185+ cm, dark reddish brown (2.5YR 3/4) clay, dark reddish (2.5YR 3/4) when dry; strong, fine, subangular blocky structure; hard, firm, very sticky, and plastic; no roots; common (ca. 25%), distinct pressure faces; common (ca. 35%), distinct and prominent cutans on ped faces; few, very fine pores; ca. 3% saprolite fragments; few, round, black (N 2/0) concretions; no effervescence with hydrogen peroxide.

SITE 16 - Wahiawa series

This site is located on a nearly level geomorphic surface on the interfluve between Poamoho Stream and its unnamed tributary to the north. At 1240 feet, the soil at Site 16 is the highest elevation Wahiawa series examined on the transect. There was no obvious discontinuity observed in this profile in the field.

Ap1 - 0 to 10 cm, dusky red (10R 3/2) silty clay, dusky red (10R 3/4) when dry; strong, very fine and fine, granular structure; slightly hard, firm, sticky, and slightly plastic; common, very fine and fine roots; strong effervescence with hydrogen peroxide; clear, wavy boundary.

Ap2 - 10 to 30 cm, dark reddish brown (2.5YR 2.5/4) clay, dark reddish brown (2.5YR 3/4) when dry; strong, coarse, subangular blocky parting to strong, very fine and fine, subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; few, fine, black (N 2/0) concretions; violent effervescence with hydrogen peroxide; clear, wavy boundary.

Ap3 - 30 to 53 cm, dark reddish brown (2.5YR 3/4) silty clay, dark red (2.5YR 3/6) when dry; massive parting to strong, very fine and fine, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots; very few, faint pressure faces; few, very fine pores; few, fine, black (N 2/0) concretions; violent effervescence with hydrogen peroxide; abrupt, wavy boundary.

Bw - 53 to 118 cm, dusky red (10R 3/4) silty clay, dark red (2.5YR 3/6) when dry; weak, moderate, prismatic parting to strong, medium to coarse, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots; few, distinct pressure faces; very few, distinct cutans; few, very fine pores; common, medium, black (N 3/0) stains on ped faces; common (ca. 5%), fine, black (N 2/0) concretions; strong effervescence with hydrogen peroxide; clear, smooth boundary.

Bt1 - 118 to 138 cm, dusky red (10R 3/4) silty clay, dark red (2.5YR 3/6) when dry; strong, very thick, vertical platy parting to strong, very fine to medium, angular blocky structure; hard, firm, sticky, and slightly plastic; no roots; few (ca. 10%), distinct pressure faces; few (ca. 15%), prominent cutans on ped faces; few, very fine pores; few, fine, black (N 3/0) stains on ped faces; many, fine, black (N 2/0) concretions; slight effervescence with hydrogen peroxide; clear, wavy boundary.

Bt2 - 138 to 170 cm, dusky red (10R 3/4) silty clay, dark red (2.5YR 3/6) when dry; strong, very thick, vertical platy parting to strong, very fine to medium, angular blocky structure; hard, firm, sticky, and slightly plastic; no roots; few (ca. 20%), distinct pressure faces; common (ca. 30%), prominent cutans on ped faces; few, very fine pores; ca. 1% saprolite fragments; few, fine, black (N 3/0) stains on ped faces; many, fine, black (N 2/0) concretions; very slight effervescence with hydrogen peroxide; diffuse, wavy boundary.

Bt3 - 170 to 200+ cm, dusky red (10R 3/4) silty clay, dark red (2.5YR 3/6) when dry; moderate, coarse, subangular blocky parting to strong, very fine and fine, subangular blocky structure; hard, firm, sticky, and slightly plastic; no roots; few (ca. 10%), distinct pressure faces; few (ca. 10%), distinct cutans on ped faces; few, very fine pores; ca. 3% saprolite fragments; few, fine, black (N 3/0) stains on ped faces; many, fine, black (N 2/0) concretions; very slight effervescence with hydrogen peroxide.

SITE 17 - Paaloa series

This site is on a gently sloping geomorphic surface on the interfluve between Poamoho Stream and its unnamed tributary to the north. The elevation is about 1310 feet.

Ap - 0 to 30 cm, dusky red (10R 3/2) clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to strong, very fine granular structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; few (ca. 10%), faint pressure faces; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

BA - 30 to 62 cm, dusky red (10R 3/3) silty clay, dark reddish brown (2.5YR 3/4) when dry; massive parting to strong, medium and coarse, subangular blocky structure; hard, firm, sticky, and plastic; few, very fine and fine roots; few (ca. 25%), faint pressure faces; few, fine pores; no effervescence with hydrogen peroxide; very abrupt, wavy boundary.

2Bt1 - 62 to 90 cm, dark reddish brown (2.5YR 3/4) clay, red (2.5YR 4/6) when dry; massive parting to strong, very fine and fine, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; common, distinct pressure faces; few (ca. 5%), faint cutans on ped faces; few, fine pores; no effervescence with hydrogen peroxide; clear, wavy boundary.

2Bt2 - 90 to 130 cm, dusky red (10R 3/4) clay, red (2.5YR 4/6) when dry; massive parting to strong, very fine and fine, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; common, distinct pressure faces; common (ca. 30%), distinct cutans on ped faces; few, fine pores; very slight effervescence with hydrogen peroxide; clear, wavy boundary.

2Bt3 - 130 to 155 cm, dark red (2.5YR 3/6) silty clay, red (2.5YR 4/6) when dry; massive parting to strong, very fine and fine, angular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots; common, distinct pressure faces; common (ca. 30%), distinct cutans on ped faces; few, fine pores; very slight effervescence with hydrogen peroxide; diffuse, wavy boundary.

2Bt4 - 155 to 190+ cm, reddish brown (2.5YR 4/4) silty clay, red (2.5YR 4/6) when dry; massive parting to strong, very fine and fine, angular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots; common, distinct pressure faces; few (ca. 20%), prominent cutans in pores and on ped faces; few, fine pores; no effervescence with hydrogen peroxide.

SITE 18 - Paaloa series

Site 18 occurs at an elevation of about 1340 feet, on the interfluve between Poamoho Stream and its unnamed tributary to the north. It is on a nearly level geomorphic surface upslope of Site 17.

Ap1 - 0 to 10 cm, very dusky red (10R 2.5/2) silty clay, dusky red (10R 3/2) when dry; strong, very fine granular structure and strong, very fine and fine subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; no effervescence with hydrogen peroxide; less than 5% gravel; abrupt, smooth boundary.

Ap2 - 10 to 20 cm, dusky red (10R 3/2) silty clay, very dusky red (10YR 2.5/2) when dry; moderate, medium and coarse, subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; no effervescence with hydrogen peroxide; less than 5% gravel; abrupt, wavy boundary.

2BA - 20 to 43 cm, dusky red (10R 3/4) clay, weak red (10R 4/4) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, very sticky, and plastic; common, very fine and fine roots; few (ca. 25%), very few, faint cutans on ped faces and pores; few, very fine and fine pores; no effervescence with hydrogen peroxide; less than 5% gravel; very abrupt, wavy boundary.

3Bt1 - 43 to 70 cm, dark reddish brown (5YR 3/3) clay, reddish brown (5YR 4/3) when dry; medium, very thick platy parting to strong, very fine and fine, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots between peds; nearly continuous pressure faces; common, prominent, dusky red (10R 3/4 and 4/6) cutans on ped faces; few, fine pores; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt2 - 70 to 87 cm, reddish brown (5YR 4/4) clay, reddish brown (5YR 5/4) when dry; massive parting to strong, very fine and fine, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots between peds; common pressure faces; few, prominent, dusky red (10R 3/4 and 4/6) cutans on ped faces; few, fine pores; less than 5% saprolite fragments; very few, shiny white specs; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt3 - 87 to 113 cm, red (2.5YR 4/6) clay, red (2.5YR 5/6) when dry; strong, medium, prismatic structure; hard, firm, very sticky, and plastic; few, very fine and fine roots between peds; common pressure faces; few, prominent, dusky red (10R 3/4 and 4/6) cutans on ped faces; few, fine pores; less than 5% saprolite fragments; very few, shiny white specs; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt4 - 113 to 139 cm, dark reddish brown (5YR 3/3) clay, reddish brown (5YR 4/3) when dry; moderate, medium, prismatic parting to strong, medium, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots between peds; common pressure faces; few, prominent, dusky red (10R 3/4 and 4/6) cutans on ped faces; few, fine pores; less than 5% saprolite fragments; very few, shiny white specs; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt5 - 139 to 185+ cm, reddish brown (5YR 4/4) clay, reddish brown (5YR 5/4) when dry; strong, thick, platy parting to strong, medium, angular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots between peds; common pressure faces; few, prominent, dusky red (10R 3/4 and 4/6) cutans on ped faces; few, fine pores; less than 5% saprolite fragments; very few, shiny white specs; no effervescence with hydrogen peroxide; clear, wavy boundary.

SITE 19 - Paaloa series

Site 19 is at an elevation of about 1380 feet on the interfluve between Poamoho Stream and its unnamed tributary to the north. It is on a gently sloping geomorphic surface upslope of Site 18.

A1 - 0 to 12 cm, dusky red (7.5YR 3/2) clay, weak red (7.5YR 5/3) when dry; strong, very fine granular structure and strong, very fine and fine subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

A2 - 12 to 28 cm, dusky red (7.5YR 3/2) clay, weak red (7.5YR 5/3) when dry; strong, very fine granular structure and strong, very fine and fine subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; few very fine pores; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

2Bt1 - 28 to 46 cm, dusky red (10R 3/3) clay, dark red (10R 3/6) when dry; strong, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; common, distinct brown (7.5YR 5/4) cutans on ped faces and pores; few, very fine pores; no effervescence with hydrogen peroxide; clear, wavy boundary.

2Bt2 - 46 to 65 cm, dusky red (10R 3/4) clay, dark red (10R 3/6) when dry; strong, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; few, distinct reddish brown (5YR 4/3) cutans on ped faces and pores; few, very fine pores; no effervescence with hydrogen peroxide; very abrupt, wavy boundary.

3Bt3A - 65 to 100 cm, dark reddish brown (2.5YR 3/4) clay, reddish brown (2.5YR 4/4) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots between peds; common, distinct dusky red (10R 3/4) cutans on ped faces; few, very fine pores; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt3B - 100 to 120 cm, reddish brown (5YR 4/4) and dusky red (10R 3/4) clay, reddish brown (5YR 4/3) and dark red (10R 3/6) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots between peds; many, prominent dusky red (10R 3/4) cutans on ped faces; few, very fine pores; no effervescence with hydrogen peroxide; diffuse, wavy boundary.

3Bt3C - 120 to 140 cm, reddish brown (5YR 4/4) and dusky red (10R 3/4) clay, reddish brown (5YR 4/3) and dark red (10R 3/6) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots between peds; many, prominent dusky red (10R 3/4) cutans on ped faces; few, very fine pores; no effervescence with hydrogen peroxide; diffuse, wavy boundary.

3Bt3D - 140 to 160 cm, yellowish red (5YR 4/6) and dusky red (10R 3/4) clay, yellowish red (5YR 5/6) and dark red (10R 3/6) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots between peds; common, prominent dusky red (10R 3/4) cutans on ped faces; few, very fine pores; no effervescence with hydrogen peroxide.

3Bt3E - 140 to 180+ cm, yellowish red (5YR 4/6) and dusky red (10R 3/4) clay, yellowish red (5YR 5/6) and dark red (10R 3/6) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots between peds; common, prominent dusky red (10R 3/4) cutans on ped faces; few, very fine pores; no effervescence with hydrogen peroxide.

SITE 20 - Paaloa series

Site 20 is at an elevation of about 1650 feet, on the interfluve between Poamoho Stream and its unnamed tributary to the north. It is on a nearly level surface on the highest geomorphic surface of this interfluve.

A1 - 0 to 3 cm, dark brown (7.5YR 3/2) clay, brown (7.5YR 4/2) when dry; strong, very fine and fine granular structure and strong, very fine and fine subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; few fine pores; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

A2 - 3 to 19 cm, very dark gray (10YR 3/1) clay, dark gray (10YR 4/1) when dry; moderate very fine subangular blocky structure; hard, firm, sticky, and slightly plastic; common, very fine and fine roots; few very fine pores; no effervescence with hydrogen peroxide; abrupt, smooth boundary.

2Bt1 - 19 to 40 cm, dark reddish gray (5YR 4/2) and dark red (2.5YR 3/6) silty clay, reddish brown (5YR 5/3) and red (2.5YR 4/6) when dry; moderate, fine and medium, subangular blocky structure; hard, firm, sticky, and slightly plastic; few, very fine and fine roots; common, very fine and fine pores; very few, faint dark reddish gray (5YR 4/2) cutans on ped faces and pores; no effervescence with hydrogen peroxide; very abrupt, wavy boundary.

3Bt2 - 40 to 62 cm, dark reddish brown (5YR 3/2) clay, dark reddish gray (5YR 4/2) when dry; strong, medium and coarse angular and subangular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; common, very fine and fine pores; common, distinct, dusky red (10R 3/4) cutans on ped faces and pores; nearly continuous pressure faces; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt3 - 62 to 97 cm, dark brown (7.5YR 3/2) clay, dark brown (7.5YR 4/2) when dry; strong, medium and coarse angular and subangular blocky structure; hard, firm, very sticky, and plastic; few, very fine and fine roots; common, very fine and fine pores; common, distinct, dark red (10R 3/6) cutans on ped faces and pores; nearly continuous pressure faces; no effervescence with hydrogen peroxide; clear, wavy boundary.

3Bt4 - 97 to 125 cm, dark brown (10YR 4/3) clay, brown (10YR 5/3) when dry; strong, medium and coarse angular and subangular blocky structure; hard, firm, very sticky, and plastic; no roots; common, very fine and fine pores; many (ca. 90%), prominent dark red (2.5YR 3/6) cutans on ped faces and pores; nearly continuous pressure faces; no effervescence with hydrogen peroxide; clear, wavy boundary.

3BCt - 125 to 140+ cm, dark brown (7.5YR 4/4) clay, brown (7.5YR 5/4) when dry; moderate, fine and medium subangular blocky structure; hard, firm, very sticky, and plastic; no roots; common, very fine and fine pores; common (ca. 45%), prominent red (10R 4/6) cutans on ped faces and pores; nearly continuous pressure faces; no effervescence with hydrogen peroxide.

Appendix C. Laboratory Data

Table 1A. Chemical Data of the Kolekole Series at Site 2.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)
	cm				cmol(+)/kg clay						
A1	0-25	3.65	3.75	-0.10	0.81	2.37	2.10	0.90	2.23	24.1	8.41
A2	25-60	3.70	3.60	0.10	0.70	1.62	2.78	0.83	2.22	26.9	8.15
2Bw1	60-85	4.10	4.50	-0.40	0.13	0.49	0.75	0.08	1.80	85.5	3.25
2Bw2	85-100	4.25	4.60	-0.35	0.16	0.51	1.31	0.28	0.37	82.4	2.36
2Bw3	100-118	4.25	4.50	-0.25	0.09	0.63	1.59	0.29	0.26	95.6	2.86
3BCt1	118-138	3.80	4.10	-0.30	0.76	0.83	0.77	0.71	1.64	32.9	4.71
3BCt2	138-160	3.50	3.80	-0.30	0.86	0.96	1.11	1.73	3.70	23.7	8.36
3BCt3	160-190+	3.30	3.90	-0.60	0.65	0.43	0.49	0.61	4.98	21.2	7.16

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al

Table 1B. Physical, Chemical, and Mineralogical Data of the Kolekole Series at Site 2.

horizon	depth	1.5MPa water	clay[1]	bd[3]	oc[4]	PO_4[6] reten.	Voigt area[7] mag	Voigt area[7] ilm
	cm	---- % ----		Mg/m^3	---- % ----			
A1	0-25	22.3	67	1.33	4.67	nd	7	27
A2	25-60	22.8	68	1.04	4.06	83	nd	nd
2Bw1	60-85	56.5	na[2]	0.65	17.38	99	nd	nd
2Bw2	85-100	52.5	na	0.82	12.05	nd	nd	nd
2Bw3	100-118	66.9	na	0.66	nd[5]	99	nt[8]	nt
3BCt1	118-138	23.2	70	1.57	nd	82	nd	nd
3BCt2	138-160	27.0	81	1.62	nd	nd	13	30
3BCt3	160-190+	27.2	82	1.60	nd	nd	nd	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) na = not applicable
(3) bd = bulk density, oven-dry basis
(4) oc = organic carbon
(5) nd = no data
(6) PO_4 reten. = phosphate retention
(7) mag = magnetite plus maghemite; ilm = ilmenite
(8) nt = not detectable

Table 2A. Chemical Data of the Wahiawa Series at Site 3A.

horizon	depth	pH_{KCl}	pH_{H2O}	delta $pH^{(1)}$	extractable bases(2) K	Na	Ca	Mg	$Al^{(3)}$	$cec^{(4)}$	$ecec^{(5)}$
	cm				cmol(+)/kg clay						
Ap	0-20	3.55	3.85	-0.30	0.69	0.40	1.33	2.68	2.68	21.2	5.43
Bw1	20-30	3.70	4.05	-0.35	0.54	1.26	1.66	0.49	1.79	17.4	5.74
Bw2A	30-55	4.80	5.25	-0.45	0.47	0.29	4.15	1.22	0.00	15.1	6.18
Bw2B	55-80	4.20	4.75	-0.55	0.35	0.41	3.76	1.16	0.15	13.6	5.83
Bw2C	80-108	3.70	4.00	-0.30	0.21	0.27	2.35	0.95	1.02	13.3	4.80
2BtA	108-128	3.55	3.85	-0.30	0.16	0.33	1.85	0.92	3.00	16.5	6.26
2BtB	128-150+	3.50	3.50	0.00	0.22	0.41	1.64	0.83	3.64	13.3	6.74

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al

Table 2B. Physical and Chemical Data of the Wahiawa series at Site 3A.

horizon	depth	1.5MPa water	clay[1]	bd[2]	oc[3]	PO_4[5] reten.
	cm	---- % ---		Mg/m^3	---- % ----	
Ap	0-20	22.1	66	1.32	1.83	nd
Bw1	20-30	26.1	78	1.25	1.29	nd
Bw2A	30-55	28.0	84	1.38	1.08	nd
Bw2B	55-80	28.3	85	1.41	1.03	49
Bw2C	80-108	29.3	88	1.31	1.07	nd
2BtA	108-128	26.3	79	1.47	nd[4]	nd
2BtB	128-150+	26.9	81	1.56	nd	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data
(5) PO_4 reten. = phosphate retention

Table 3A. Chemical Data of the Manana Series at Site 9.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)	oxal(6) Fe
	cm				---------- cmol(+)/kg clay						----------	%
Ap1	0-12	4.10	4.10	0.00	0.76	1.41	2.09	1.78	0.72	24.9	6.65	nd(7)
Ap2	12-30	3.95	4.10	-0.15	0.34	0.77	1.63	0.42	1.42	24.5	4.58	nd
Bt1	30-47	3.95	4.00	-0.05	0.13	0.57	0.95	0.16	2.65	22.1	4.46	nd
Bt2	47-82	3.95	3.85	0.10	0.11	0.91	1.03	0.23	2.97	16.8	5.25	1.39
Bt3	82-91	3.80	3.80	0.00	0.08	0.66	0.90	0.25	3.26	18.2	5.15	nd
2Bt4	91-150	3.80	3.80	0.00	0.10	0.53	0.92	0.44	3.40	15.8	5.39	0.08
2BCt	150-200+	3.70	3.55	0.15	0.22	1.82	0.72	0.59	3.77	14.2	7.12	nd

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al
(6) oxal Fe = acid oxalate extractable iron
(7) nd = no data

Table 3B. Physical, Chemical, and Mineralogical Data of the Manana Series at Site 9.

horizon	depth	1.5MPa water	clay[1]	bd[2]	oc[3]	PO_4[5] reten.	Voigt area[6] mag	Voigt area[6] ilm
	cm	---- %	---	Mg/m^3	---- %	---		
Ap1	0-12	22.8	68	1.13	2.04	nd	nd	nd
Ap2	12-30	21.5	65	1.47	2.65	nd	13	29
Bt1	30-47	32.6	98	1.23	2.38	nd	nd	nd
Bt2	47-82	31.6	95	1.30	1.57	56	2	6
Bt3	82-91	28.7	86	1.25	1.33	nd	nd	nd
2Bt4	91-150	27.8	83	1.56	nd[4]	nd	5	21
2BCt	150-200+	31.4	94	1.46	nd	nd	nd	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data
(5) PO_4 reten. = phosphate retention
(6) mag = magnetite plus maghemite; ilm = ilmenite

Table 4A. Chemical Data of the Wahiawa Series at Site 10.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)
	cm				cmol(+)/kg clay						
Ap	0-28	4.05	4.65	-0.60	0.39	0.38	3.65	0.51	1.33	16.2	6.26
Bw1	28-56	3.70	4.30	-0.60	0.36	0.27	2.07	0.34	3.08	14.1	6.12
Bw2	56-60	3.75	4.10	-0.35	0.24	0.26	0.89	0.12	4.25	22.9	5.76
2Bw3	60-75	3.60	4.20	-0.80	0.29	0.25	0.95	0.14	4.09	17.5	5.72
2Bw4	75-88	3.65	4.15	-0.50	0.36	0.31	0.74	0.13	4.29	17.2	5.83
2Bw5	88-105+	3.70	4.15	-0.45	0.29	0.49	0.55	0.13	3.87	13.7	5.33

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al

Table 4B. Physical and Chemical Data of the Wahiawa Series at Site 10.

horizon	depth	1.5MPa water	clay(1)	bd(2)	oc(3)
	cm	----	% ----	Mg/m^3	%
Ap	0-28	29.1	87	1.47	2.14
Bw1	28-56	34.6	100	1.32	1.17
Bw2	56-60	37.2	100	1.10	2.05
2Bw3	60-75	35.3	100	1.30	1.05
2Bw4	75-88	35.5	100	1.28	0.92
2Bw5	88-105+	35.4	100	1.31	0.88

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon

Table 5A. Chemical Data of the Wahiawa Series at Site 11.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH[1]	extractable bases[2] K	Na	Ca	Mg	Al[3]	cec[4]	ecec[5]	oxal[6] Fe
	cm				cmol(+)/kg clay							%
Ap1	0-30	4.05	4.95	-0.90	0.61	0.41	3.69	0.77	0.62	17.8	6.10	nd[7]
Ap2	30-43	3.80	4.30	-0.50	0.38	0.33	0.85	0.18	3.27	16.0	5.01	nd
Bw	43-53	3.85	4.25	-0.40	0.31	0.39	0.73	0.16	3.68	17.0	5.27	0.42
Bt1	53-84	4.00	4.75	-0.75	0.41	0.27	1.75	0.54	1.56	17.9	4.53	0.88
Bt2	84-87	4.15	4.80	-0.65	0.50	0.93	1.93	0.58	1.33	19.8	5.27	nd
2Bt3	87-103	4.15	5.00	-0.85	0.53	0.56	2.56	0.82	0.85	15.4	5.32	0.18
2Bt4	103-127+	4.05	4.95	-0.90	0.42	0.35	2.18	0.86	1.03	14.3	4.84	0.38

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al
(6) oxal Fe = acid oxalate extractable iron
(7) nd = no data

Table 11B. Physical and Chemical Data of the Paaloa Series at Site 17.

horizon	depth	1.5MPa water	clay[1]	bd[2]	oc[3]
	cm	---- %	---	Mg/m^3	%
Ap	0-30	29.5	88	1.49	3.27
BA	30-62	35.0	100	1.36	2.40
2Bt1	62-90	34.1	100	1.35	1.07
2Bt2	90-130	36.6	100	1.38	0.94
2Bt3	130-155	32.9	100	1.33	nd[4]
2Bt4	155-190+	41.8	100	1.41	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data

Table 12A. Chemical Data of the Paaloa Series at Site 18.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)
	cm				cmol(+)/kg clay						
Ap1	0-10	4.00	4.60	-0.60	0.33	0.29	1.25	0.40	1.59	20.4	3.86
Ap2	10-20	3.95	4.60	-0.65	0.23	0.37	1.18	0.26	1.63	17.0	3.67
BAt	20-43	4.15	4.85	-0.70	0.03	0.32	0.69	0.12	1.18	16.4	2.34
2Bt1	43-70	3.95	4.85	-0.90	0.07	0.38	0.79	0.11	1.74	11.7	3.09
2Bt2	70-87	3.90	4.85	-0.95	0.05	0.30	1.02	0.12	1.68	14.8	3.17
2Bt3	87-113	3.90	4.75	-0.85	0.01	0.24	1.10	0.12	1.81	21.0	3.28
2Bt4	113-139	3.80	4.70	-0.90	0.10	0.84	0.98	0.13	1.91	19.9	3.96
2Bt5	139-185+	3.85	4.65	-0.80	0.01	0.26	0.79	0.13	1.30	25.3	2.47

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al

Table 12B. Physical and Chemical Data of the Paaloa series at Site 18.

horizon	depth	1.5MPa water	clay(1)	bd(2)	oc(3)
	cm	---- %	---	Mg/m^3	%
Ap1	0-10	29.2	88	1.48	3.13
Ap2	10-20	29.6	89	1.51	3.11
BAt	20-43	36.2	100	1.30	2.59
2Bt1	43-70	39.6	100	1.39	1.24
2Bt2	70-87	37.3	100	1.40	1.10
2Bt3	87-113	38.2	100	1.41	0.95
2Bt4	113-139	36.5	100	1.45	nd(4)
2Bt5	139-185+	36.9	100	1.40	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data

Table 13A. Chemical Data of the Paaloa Series at Site 19.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)	oxal(6) Fe
	cm				cmol(+)/kg clay							%
A1	0-12	3.75	4.70	-0.95	0.87	1.04	0.95	1.16	1.60	20.5	5.62	nd(7)
A2	12-28	3.65	4.50	-0.85	0.50	0.57	0.22	0.52	2.48	18.8	4.29	2.09
2Bt1	28-46	4.00	4.45	-0.45	0.21	0.31	0.07	0.09	2.07	21.3	2.75	nd
2Bt2	46-65	4.00	4.50	-0.50	0.18	0.30	0.07	0.09	1.85	17.7	2.49	1.58
3Bt3A	65-100	4.20	4.45	-0.25	0.01	0.31	0.04	0.08	0.71	7.6	1.15	0.39
3Bt3B	100-120	4.35	4.80	-0.45	0.02	0.25	0.04	0.09	0.57	8.7	0.97	nd
3Bt3C	120-140	4.40	4.80	-0.40	0.01	0.21	0.04	0.10	0.69	10.6	1.04	nd
3Bt3D	140-160	4.35	4.85	-0.50	0.06	0.89	0.07	0.11	0.36	12.8	1.49	nd
3Bt3E	160-180+	4.30	4.75	-0.45	0.01	0.16	0.05	0.09	0.62	16.2	0.92	0.27

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al
(6) oxal Fe = acid oxalate extractable iron
(7) nd = no data

Table 13B. Physical, Chemical, and Mineralogical Data of the Paaloa Series at Site 19.

horizon	depth	1.5MPa water	clay[1]	bd[2]	oc[3]	Voigt area[5] mag	Voigt area[5] ilm
	cm	---- %	---	Mg/m^3	%		
A1	0-12	25.4	76	1.60	3.35	nd	nd
A2	12-28	25.3	76	1.65	2.67	10	105
2Bt1	28-46	28.1	84	1.43	2.50	3	6
2Bt2	46-65	27.2	82	1.50	2.19	nd	nd
3Bt3A	65-100	27.2	82	1.46	1.21	11	27
3Bt3B	100-120	30.9	93	1.37	nd[4]	nd	nd
3Bt3C	120-140	29.4	88	1.53	nd	nd	nd
3Bt3D	140-160	30.2	91	1.48	nd	nd	nd
3Bt3E	160-180+	33.0	99	1.48	nd	nd	nd

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data
(5) mag = magnetite plus maghemite; ilm = ilmenite

Table 14A. Chemical Data of the Paaloa Series at Site 20.

horizon	depth	pH_{KCl}	pH_{H2O}	delta pH(1)	extractable bases(2) K	Na	Ca	Mg	Al(3)	cec(4)	ecec(5)	oxal(6) Fe
	cm				-------------- cmol(+)/kg clay						-------------	%
A1	0-3	4.20	4.25	-0.05	0.21	0.73	0.49	0.43	0.94	22.0	2.80	nd(7)
A2	3-19	4.05	4.00	0.05	0.09	0.46	0.28	0.18	0.87	22.7	1.88	nd
2Bt1	19-40	4.25	4.20	0.05	0.19	0.45	0.13	0.14	0.47	17.9	1.36	1.35
3Bt2	40-62	4.25	4.45	-0.20	0.02	0.18	0.15	0.15	0.73	9.8	1.23	0.25
3Bt3	62-97	4.30	4.70	-0.40	0.02	0.63	0.07	0.17	0.52	9.8	1.41	nd
3Bt4	97-125	4.25	4.95	-0.70	0.01	0.43	0.05	0.14	0.33	8.0	0.99	nd
3BCt	125-140+	4.45	4.90	-0.45	0.00	0.29	0.07	0.13	0.22	10.0	0.71	nd

(1) delta pH = pH(KCl) - pH(water)
(2) bases extracted with 1N ammonium acetate at pH 7
(3) aluminum extracted with 1N KCl
(4) cec = cation exchange capacity by ammonium acetate at pH 7
(5) ecec = effective cation exchange capacity = sum of ammonium acetate extractable bases plus 1N KCl extractable Al
(6) oxal Fe = acid oxalate extractable iron
(7) nd = no data

Table 14B. Physical and Chemical Data of the Paaloa series at Site 20.

horizon	depth	1.5MPa water	clay[1]	bd[2]	oc[3]
	cm	---- %	---	Mg/m^3	%
A1	0-3	22.0	66	1.65	3.32
A2	3-19	21.3	64	1.65	2.91
2Bt1	19-40	35.7	100	1.34	2.79
3Bt2	40-62	33.6	100	1.49	1.56
3Bt3	62-97	38.0	100	1.49	1.30
3Bt4	97-125	34.4	100	1.35	1.16
3BCt	125-140+	32.4	97	1.47	nd[4]

(1) (percent 1.5MPa water) x 3 = estimated percent clay
(2) bd = bulk density, oven-dry basis
(3) oc = organic carbon
(4) nd = no data

Appendix D. Ammonium oxalate extractable silica, iron and aluminum from the Kolekole series at Sites 1A and 1B.

		oxalate extractable			Al plus
site	horizon	Si (%)	Fe (%)	Al (%)	1/2 Fe (%)
Site 1A	Ap	0.47	0.37	1.87	2.06
	Bw1	0.04	0.52	0.64	0.90
	Bw2	0.53	0.55	2.34	2.62
	Bw3	1.65	0.52	5.63	5.89
	2BCt1	0.15	0.05	0.65	0.68
	Bw4	1.67	0.47	5.69	5.93
	2BCt2	0.04	0.07	0.32	0.36
Site 1B	Ap	0.16	0.83	1.20	1.62
	Bw1	0.42	0.76	2.47	2.85
	Bw2	1.25	0.73	5.98	6.35
	Bw3	1.13	0.71	5.38	5.74
	2BCt1	0.15	0.15	0.85	0.93
	2BCt2	0.03	0.14	0.45	0.52

Appendix E. X-ray Diffractograms

Key: K,DH - kaolinite, dehydrated halloysite
G - gibbsite
Q - quartz
M - magnetite and/or maghemite
I - ilmenite

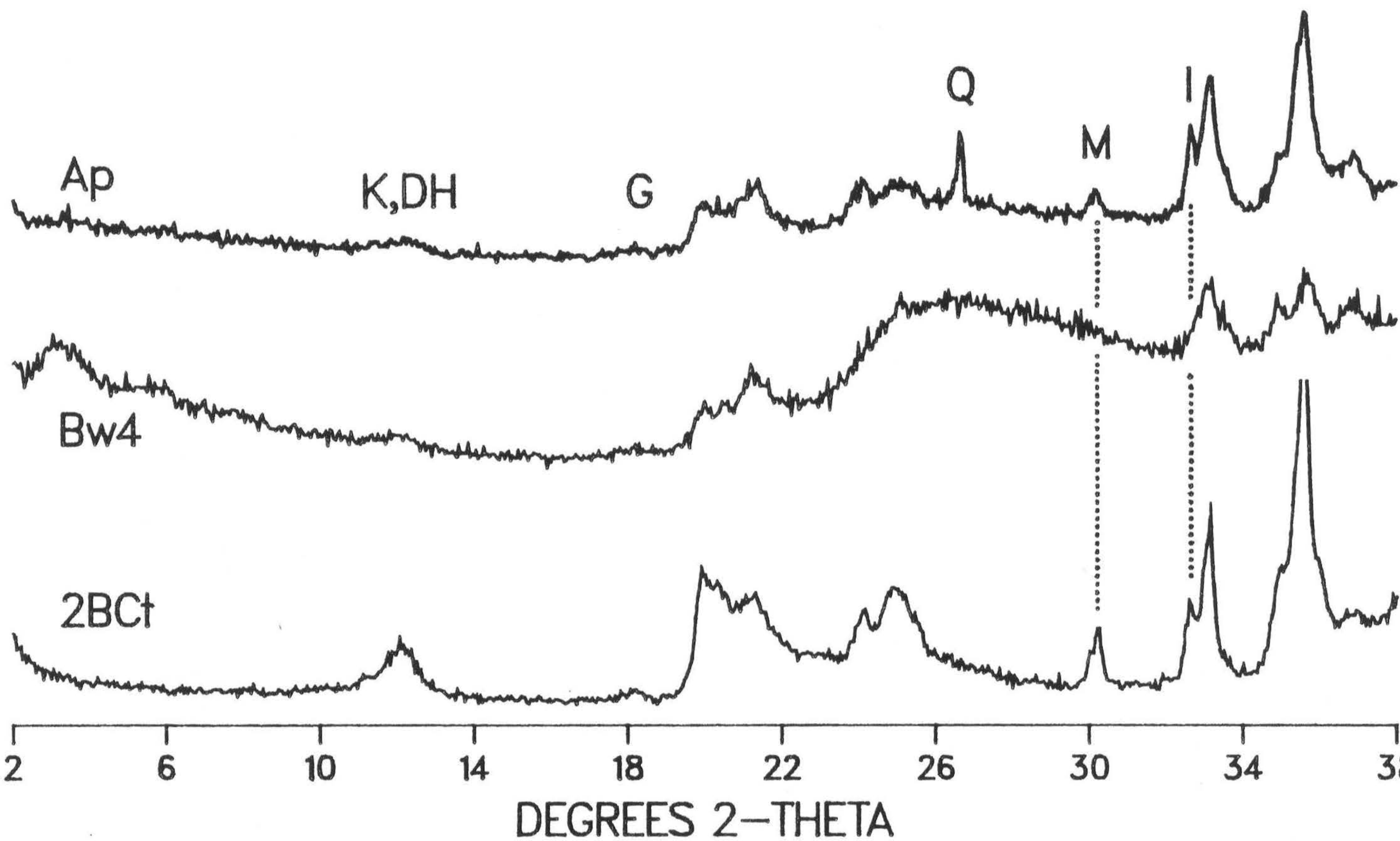

Figure 28. X-ray diffractograms of the Ap, Bw4, and 2BCt horizons of the Kolekole series at Site 1A. Magnetite and ilmenite peaks are indicated by the dotted lines.

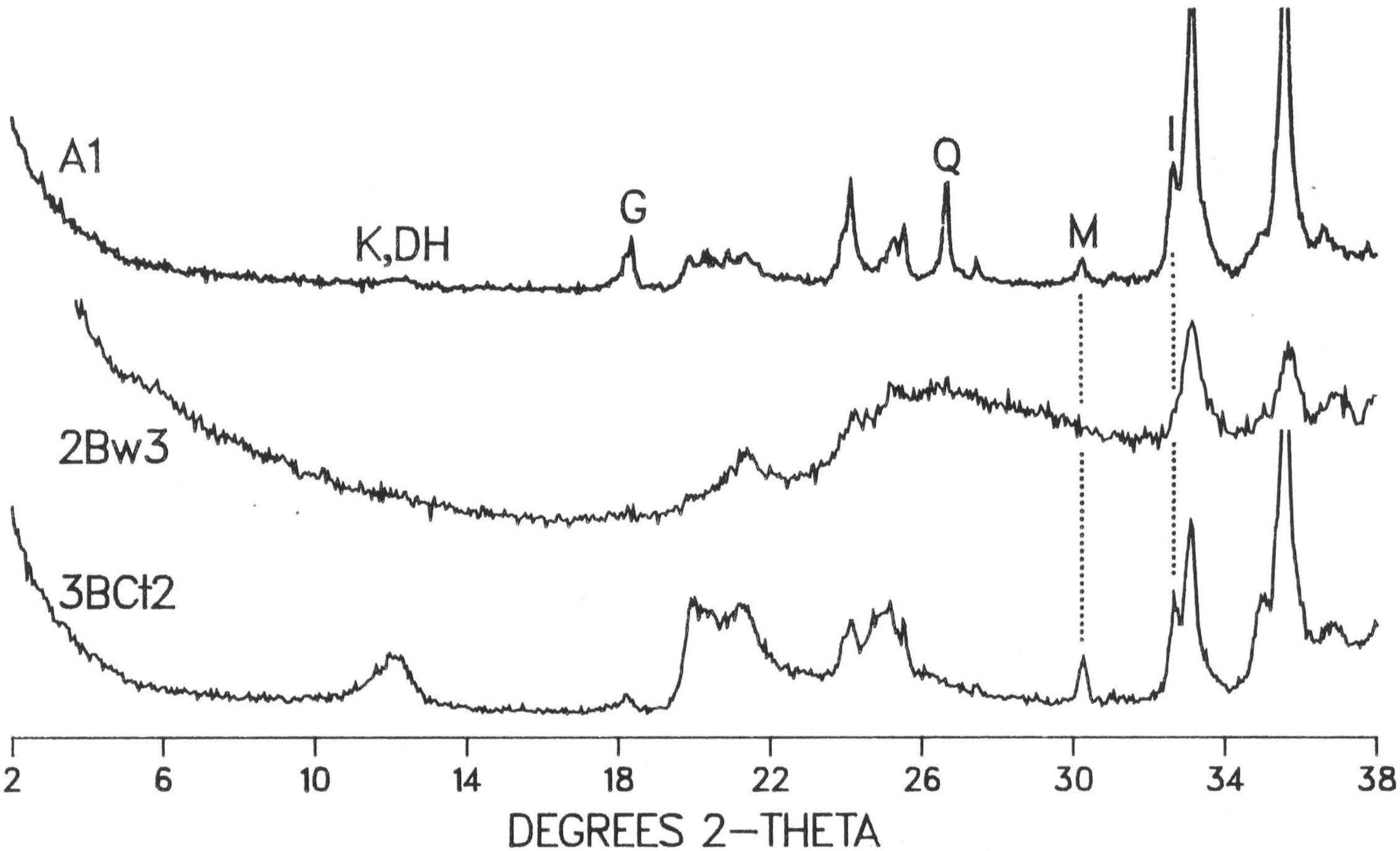

Figure 29. X-ray diffractograms of the A1, 2Bw3, and 3BCt2 horizons of the Kolekole series at Site 2. Magnetite and ilmenite peaks are indicated by the dotted lines.

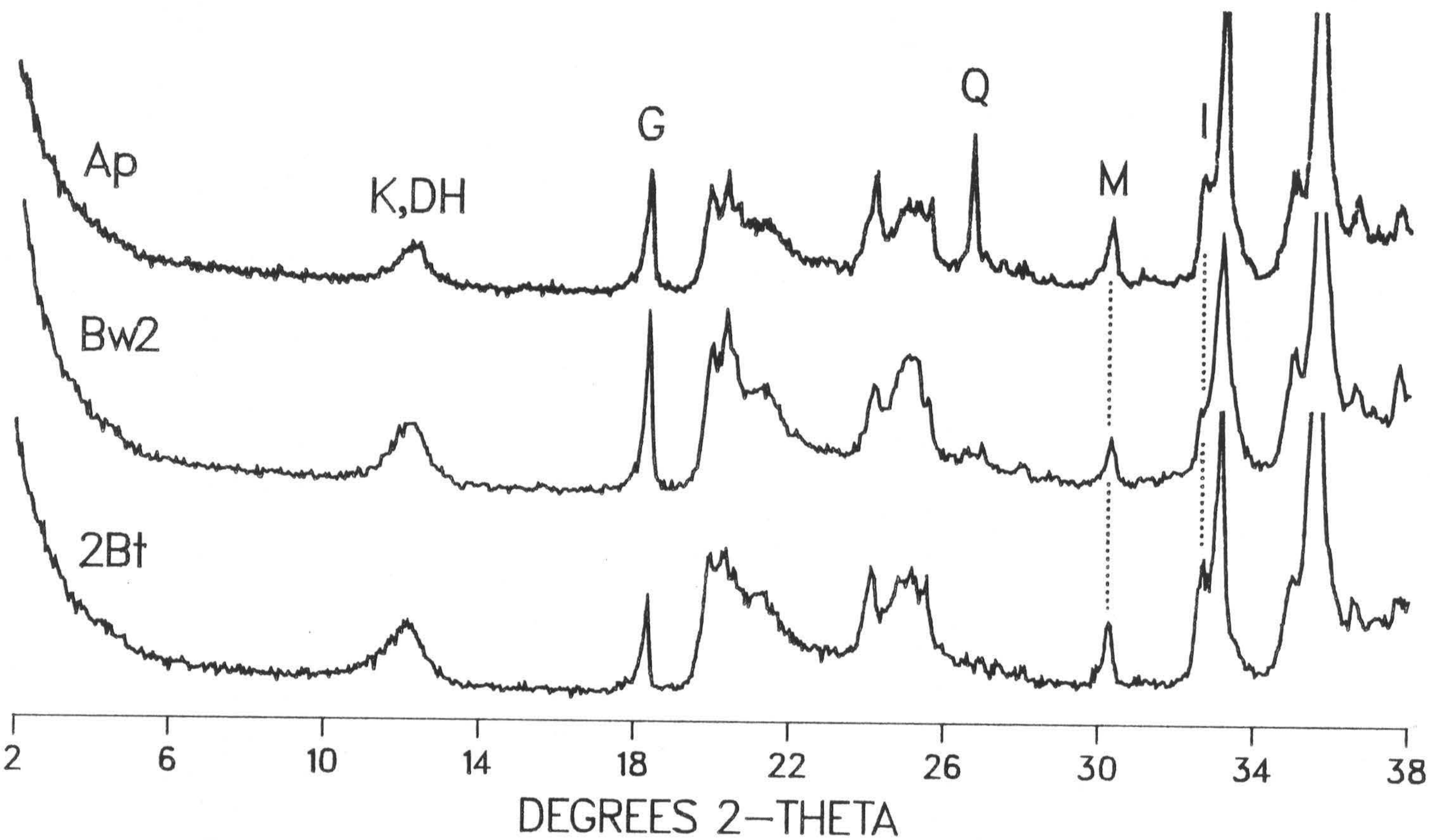

Figure 30. X-ray diffractograms of the Ap, Bw2, and 2Bt horizons of the Wahiawa series at Site 3A. Magnetite and ilmenite peaks are indicated by the dotted lines.

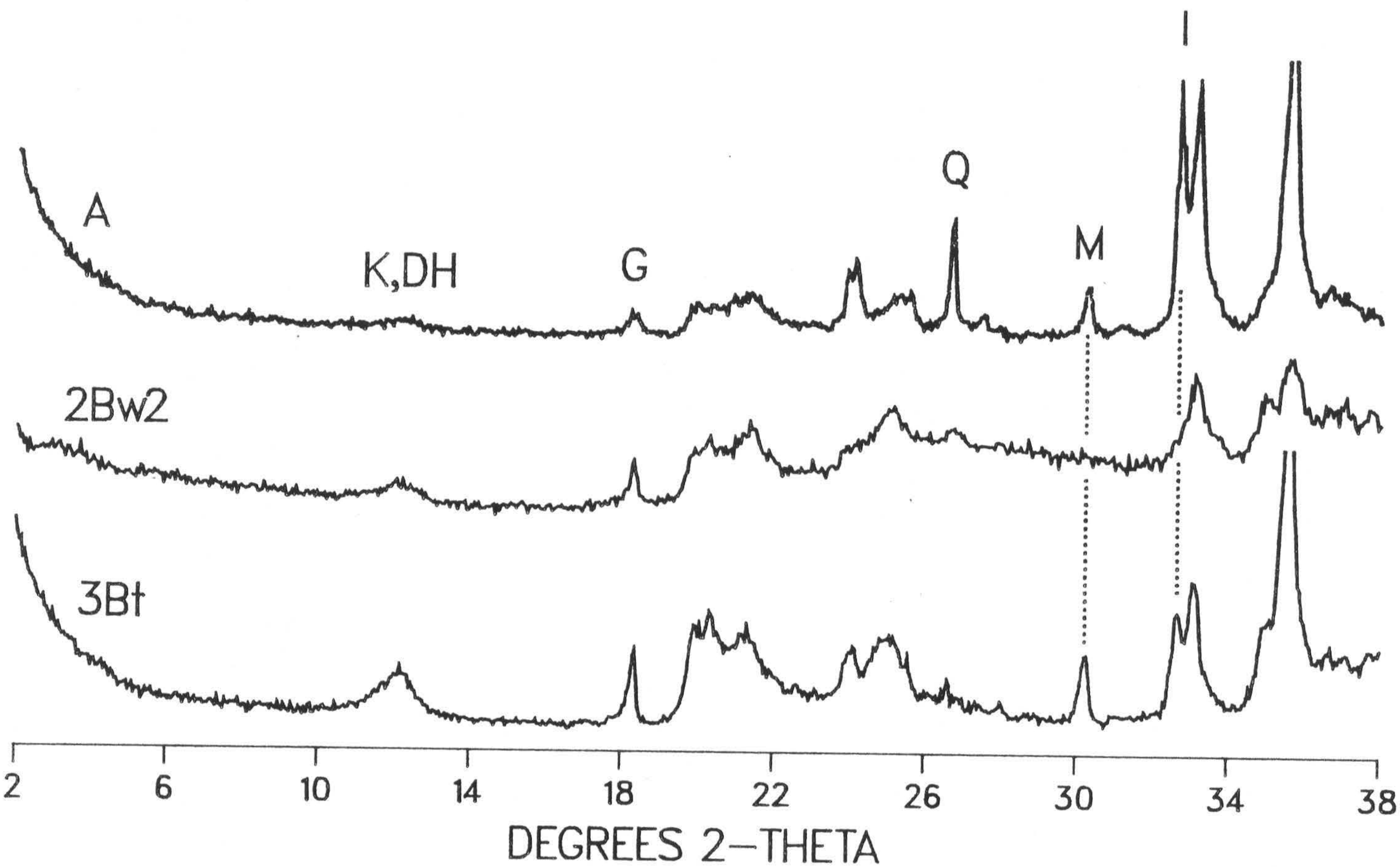

Figure 31. X-ray diffractograms of the A, 2Bw2, and 3Bt horizons of the Wahiawa series at Site 4. Magnetite and ilmenite peaks are indicated by the dotted lines.

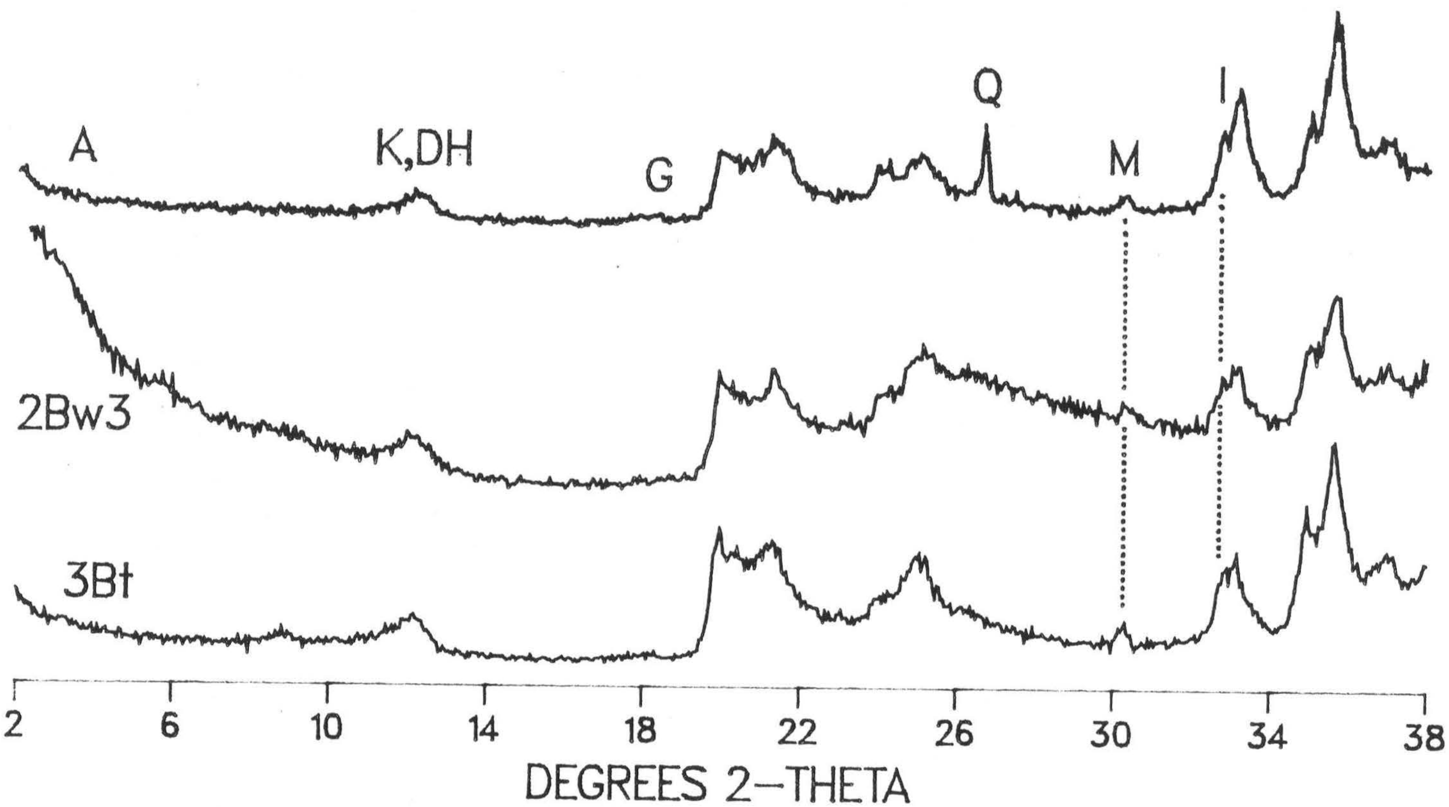

Figure 32. X-ray diffractograms of the A, 2Bw3, and 3Bt horizons of the Wahiawa series at Site 5. Magnetite and ilmenite peaks are indicated by the dotted lines.

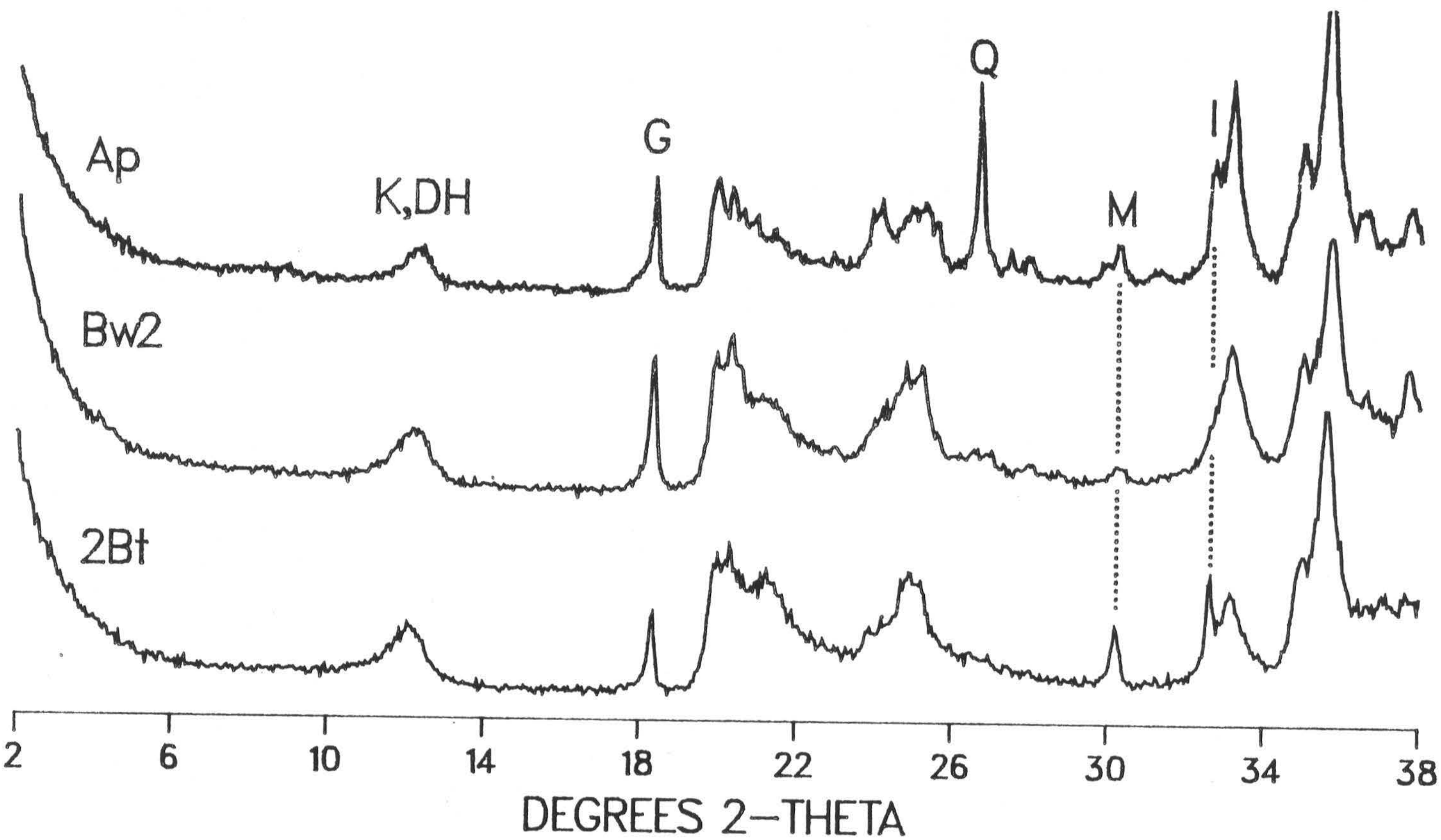

Figure 33. X-ray diffractograms of the Ap, Bw2, and 2Bt horizons of the Wahiawa series at Site 6. Magnetite and ilmenite peaks are indicated by the dotted lines.

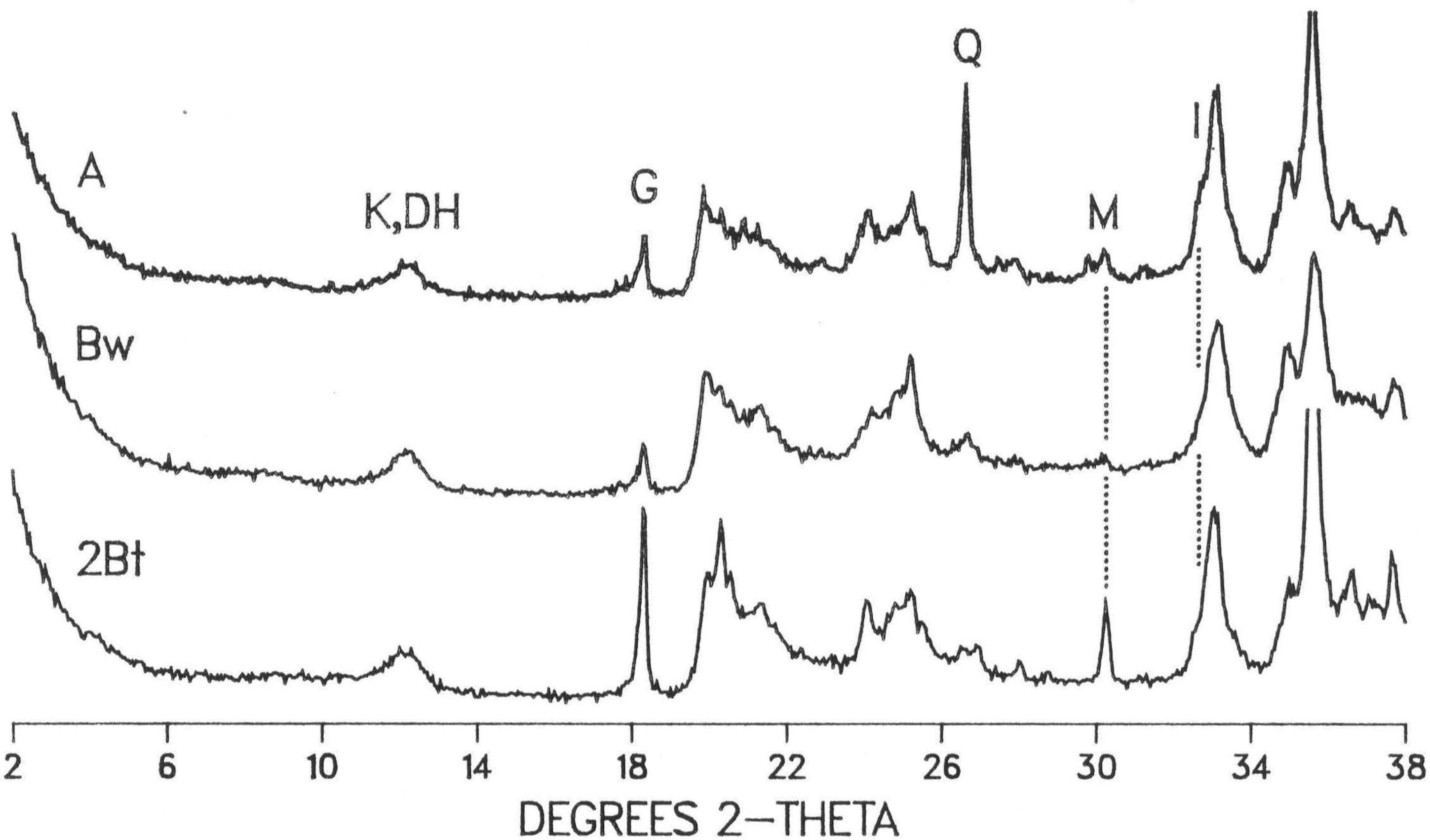

Figure 34. X-ray diffractograms of the A, Bw, and 2Bt horizons of the Wahiawa series at Site 7. Magnetite and ilmenite peaks are indicated by the dotted lines.

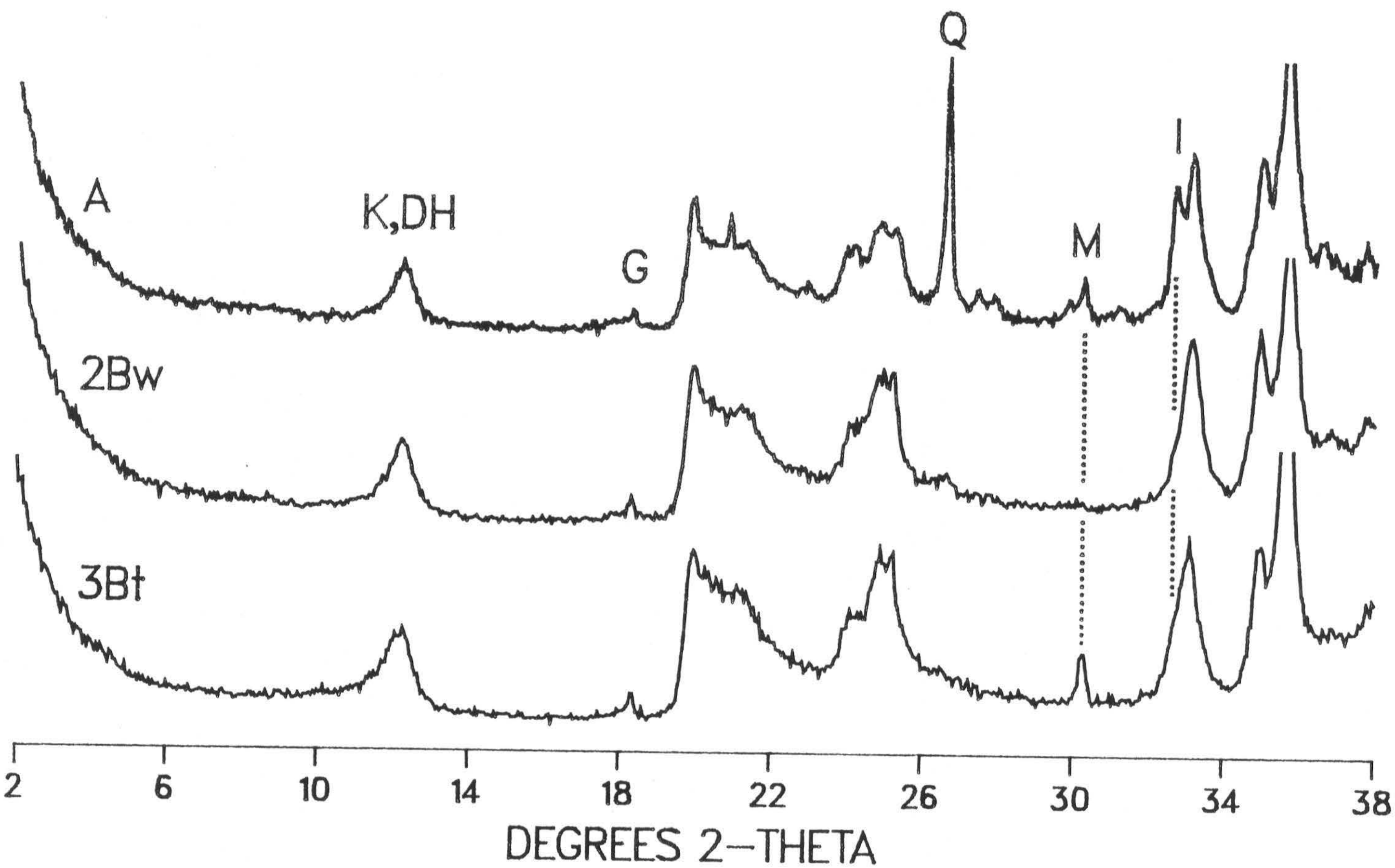

Figure 35. X-ray diffractograms of the A, 2Bw, and 3Bt horizons of the Kolekole series at Site 8. Magnetite and ilmenite peaks are indicated by the dotted lines.

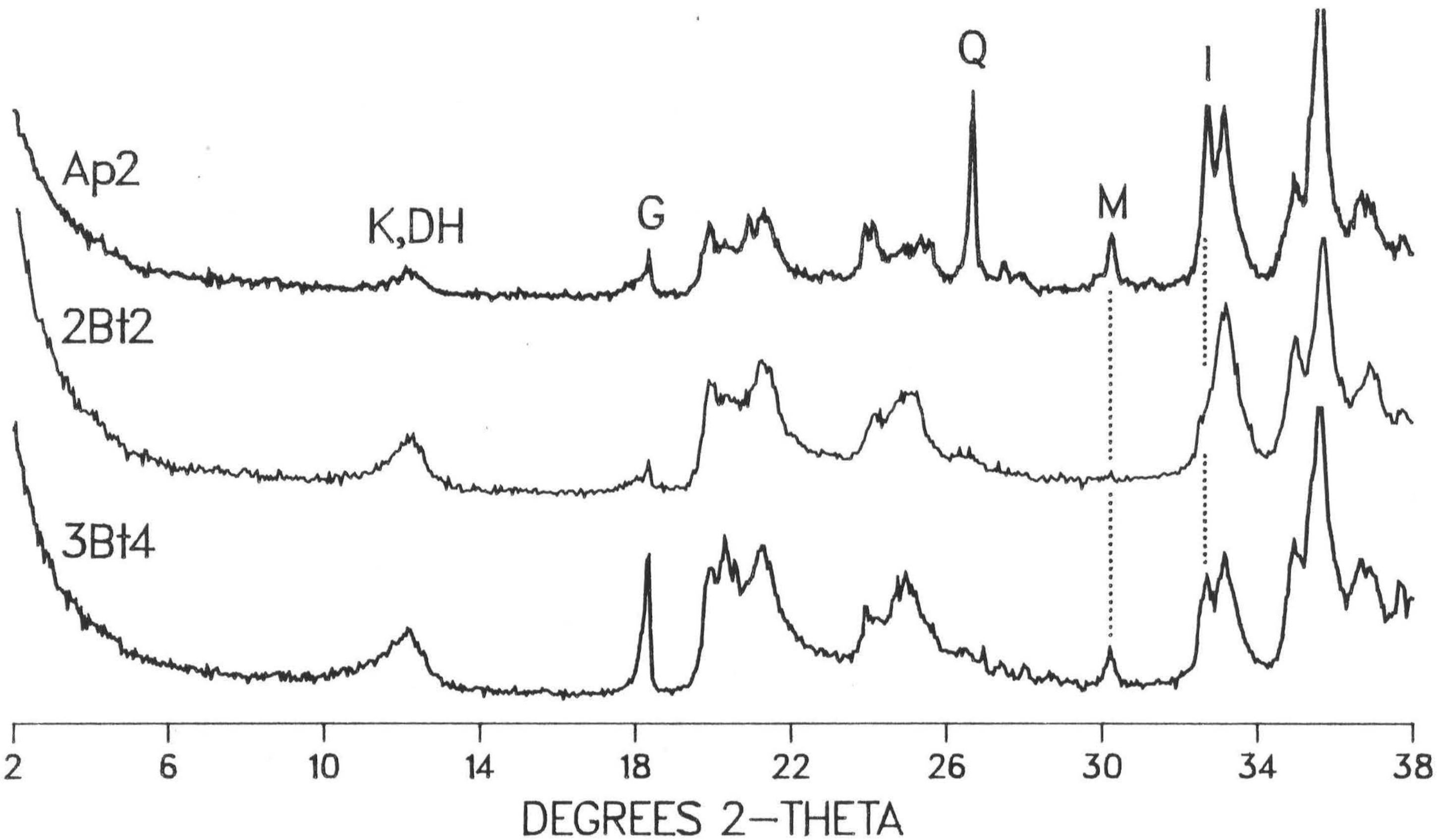

Figure 36. X-ray diffractograms of the Ap2, 2Bt2, and 3Bt4 horizons of the Manana series at Site 9. Magnetite and ilmenite peaks are indicated by the dotted lines.

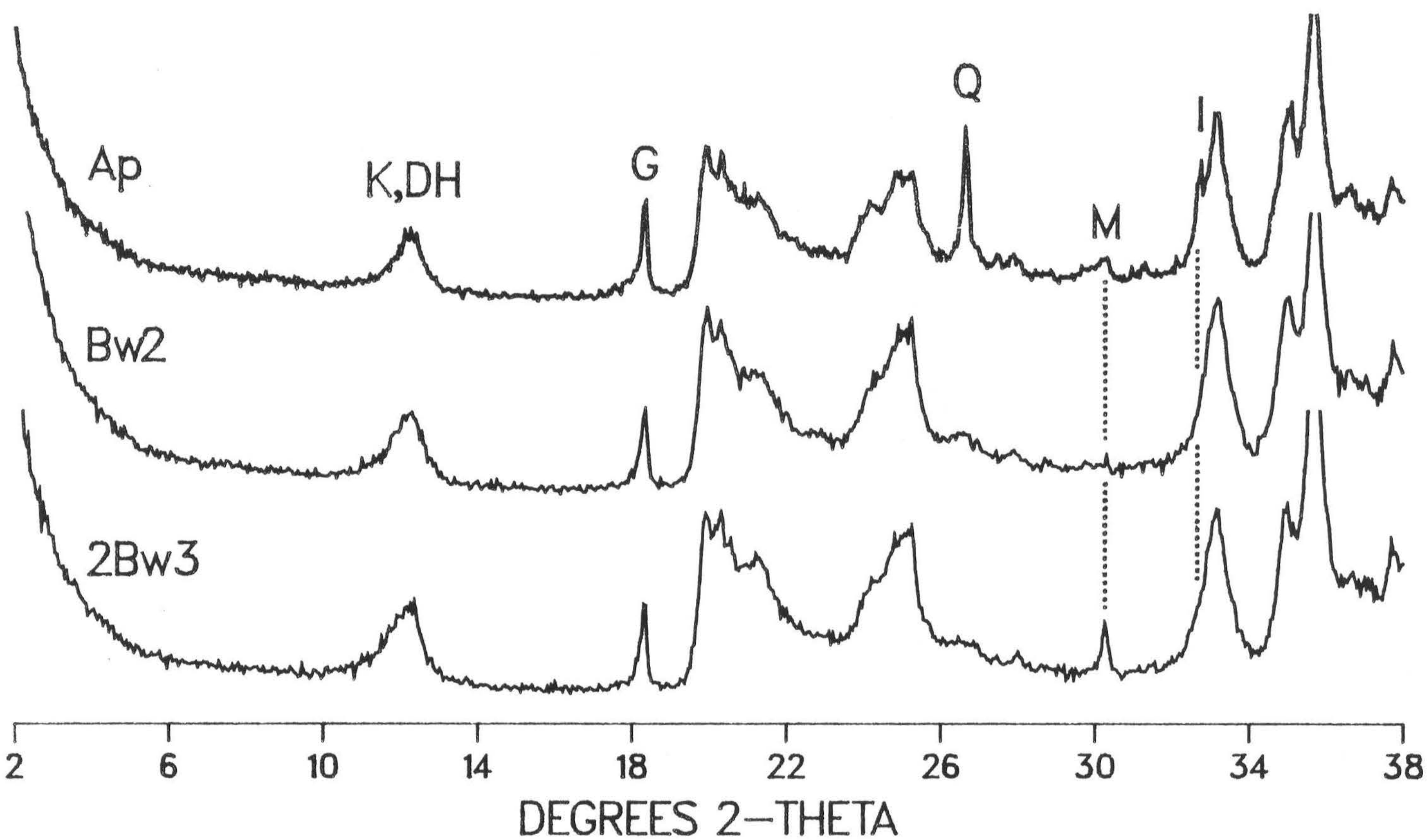

Figure 37. X-ray diffractograms of the Ap, Bw2, and 2Bw3 horizons of the Wahiawa series at Site 10. Magnetite and ilmenite peaks are indicated by the dotted lines.

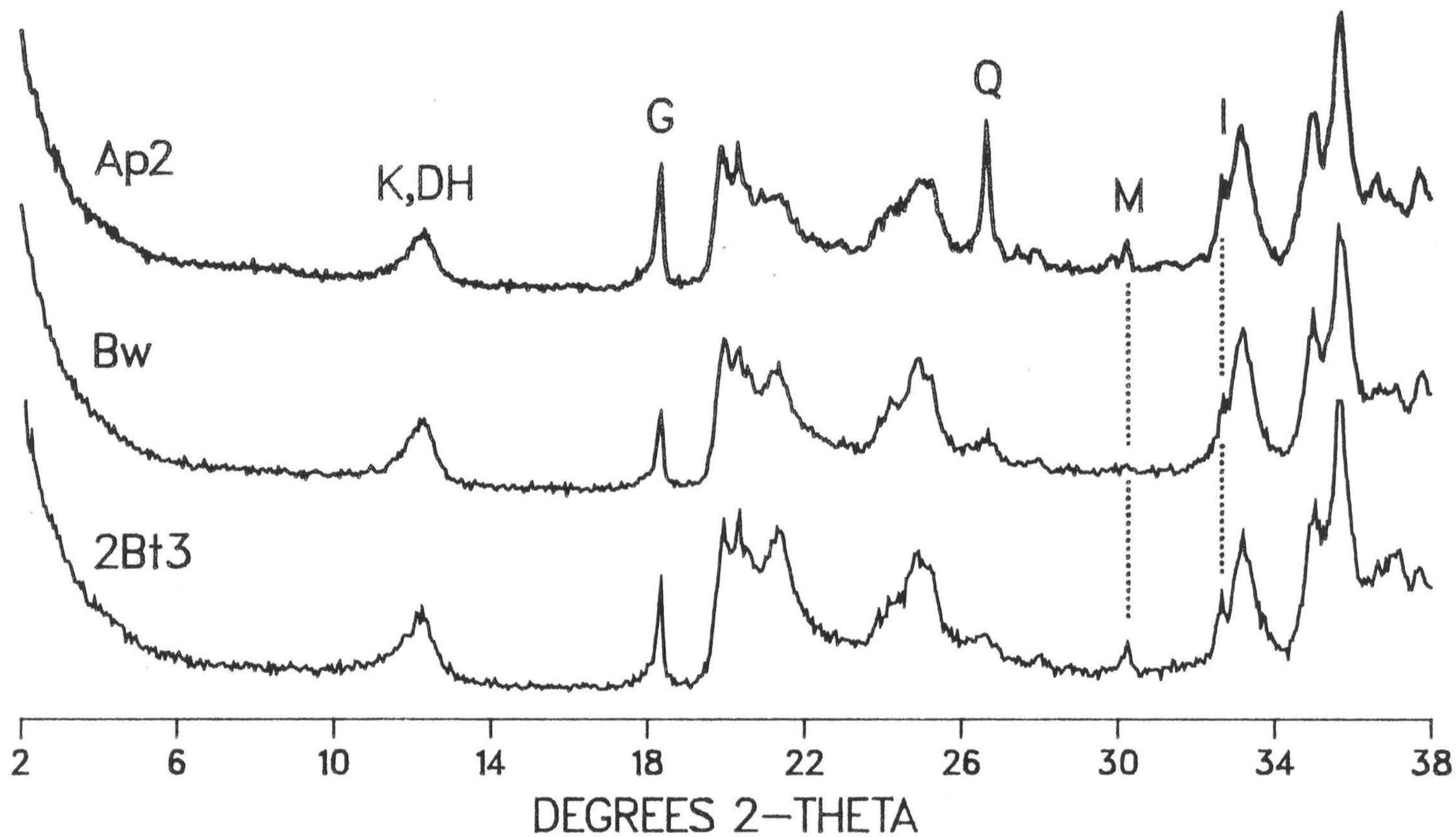

Figure 38. X-ray diffractograms of the Ap2, Bw, and 2Bt3 horizons of the Wahiawa series at Site 11. Magnetite and ilmenite peaks are indicated by the dotted lines.

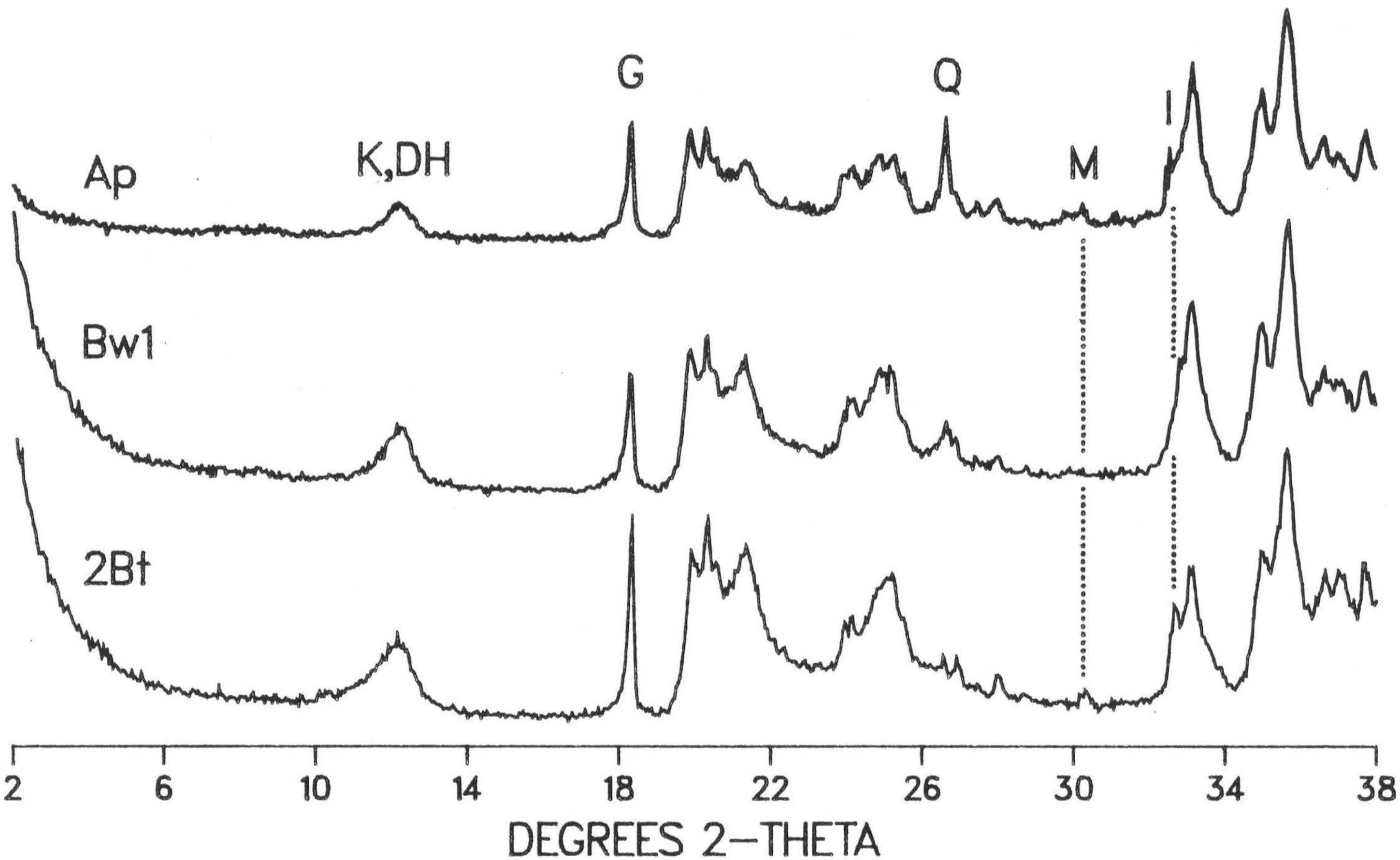

Figure 39. X-ray diffractograms of the Ap, Bwl, and 2Bt horizons of the Wahiawa series at Site 12. Magnetite and ilmenite peaks are indicated by the dotted lines.

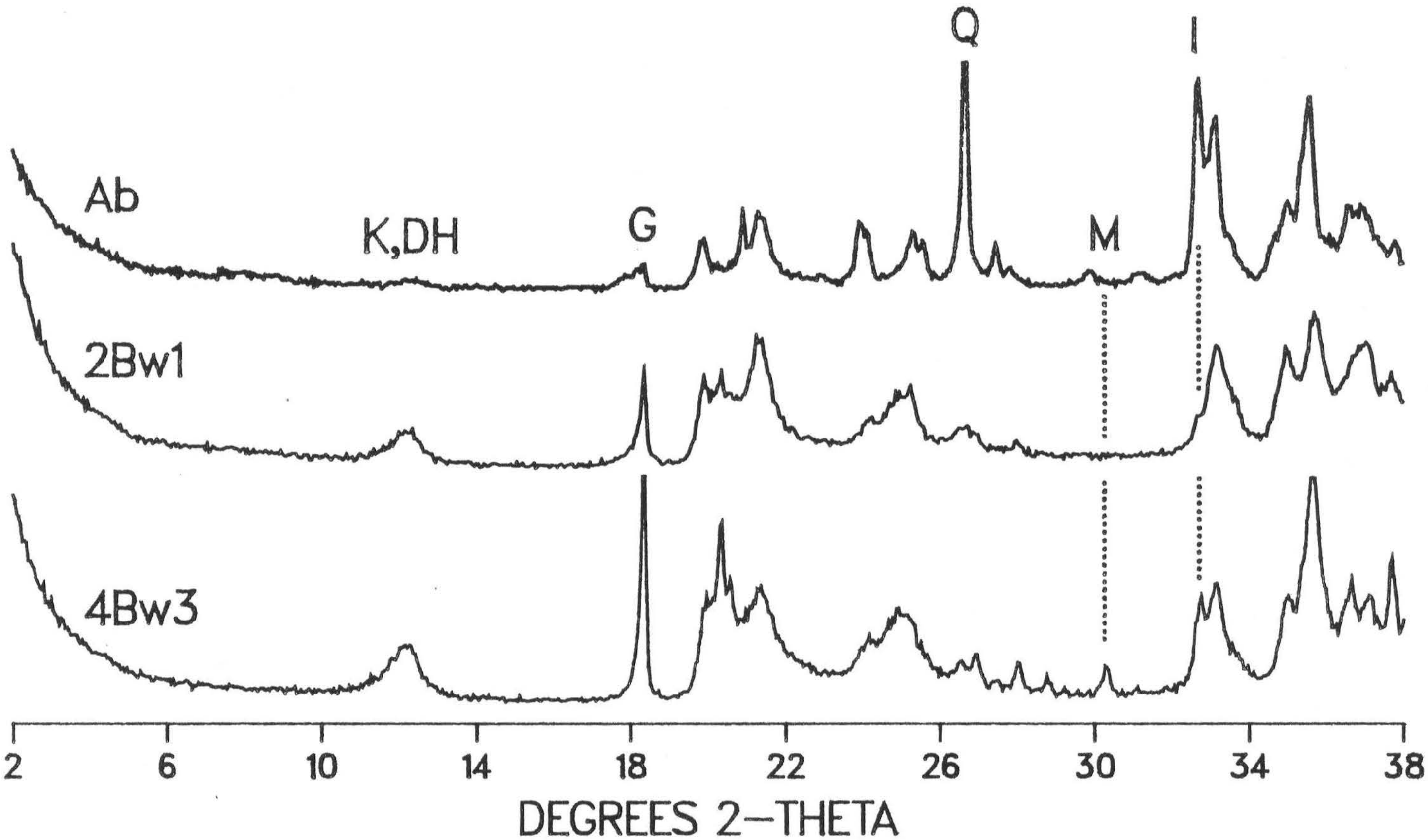

Figure 40. X-ray diffractograms of the Ab, 2Bw3, and 4Bw3 horizons of the Wahiawa series at Site 13. Magnetite and ilmenite peaks are indicated by the dotted lines.

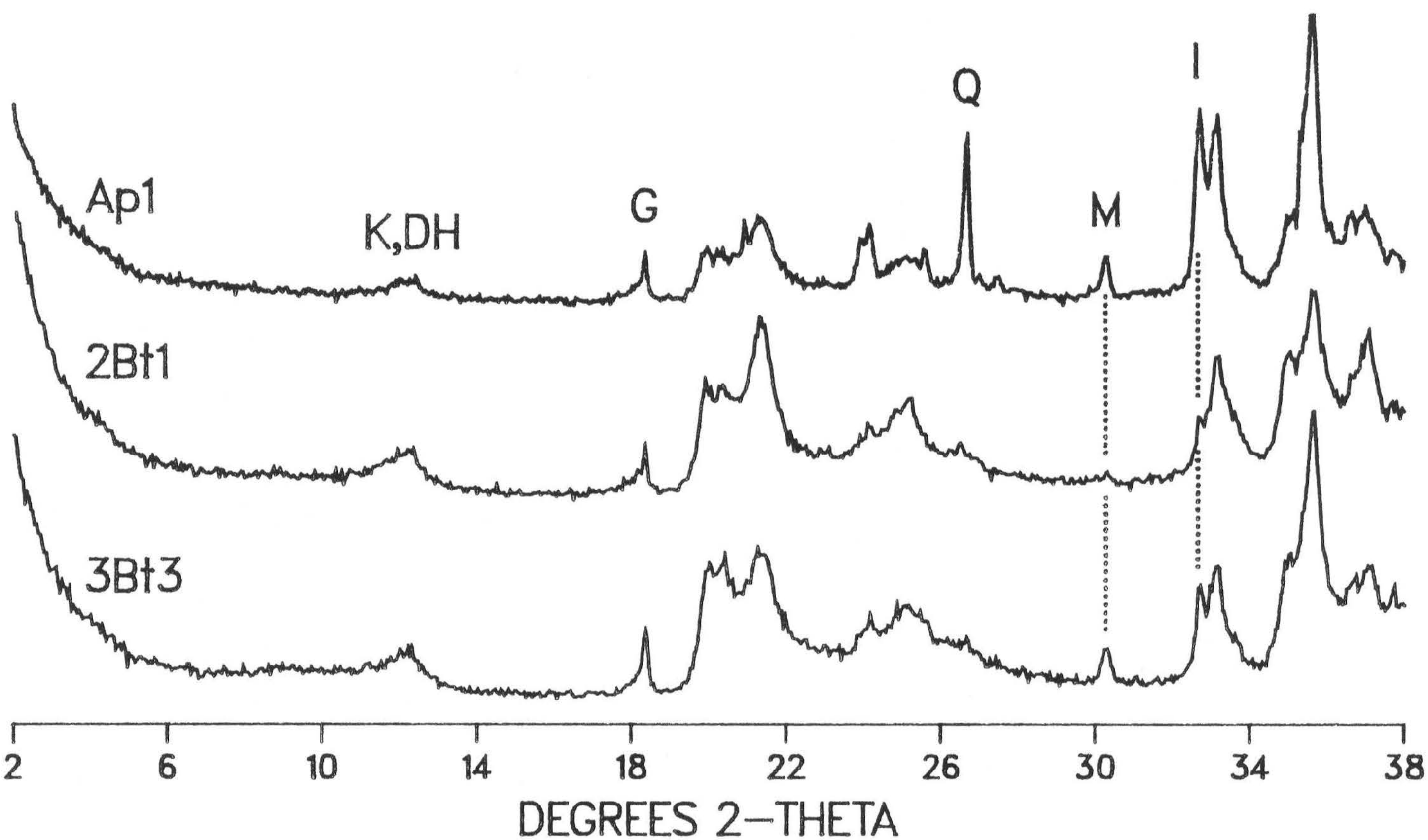

Figure 41. X-ray diffractograms of the Ap1, 2Bt1, and 3Bt3 horizons of the Wahiawa series at Site 14. Magnetite and ilmenite peaks are indicated by the dotted lines.

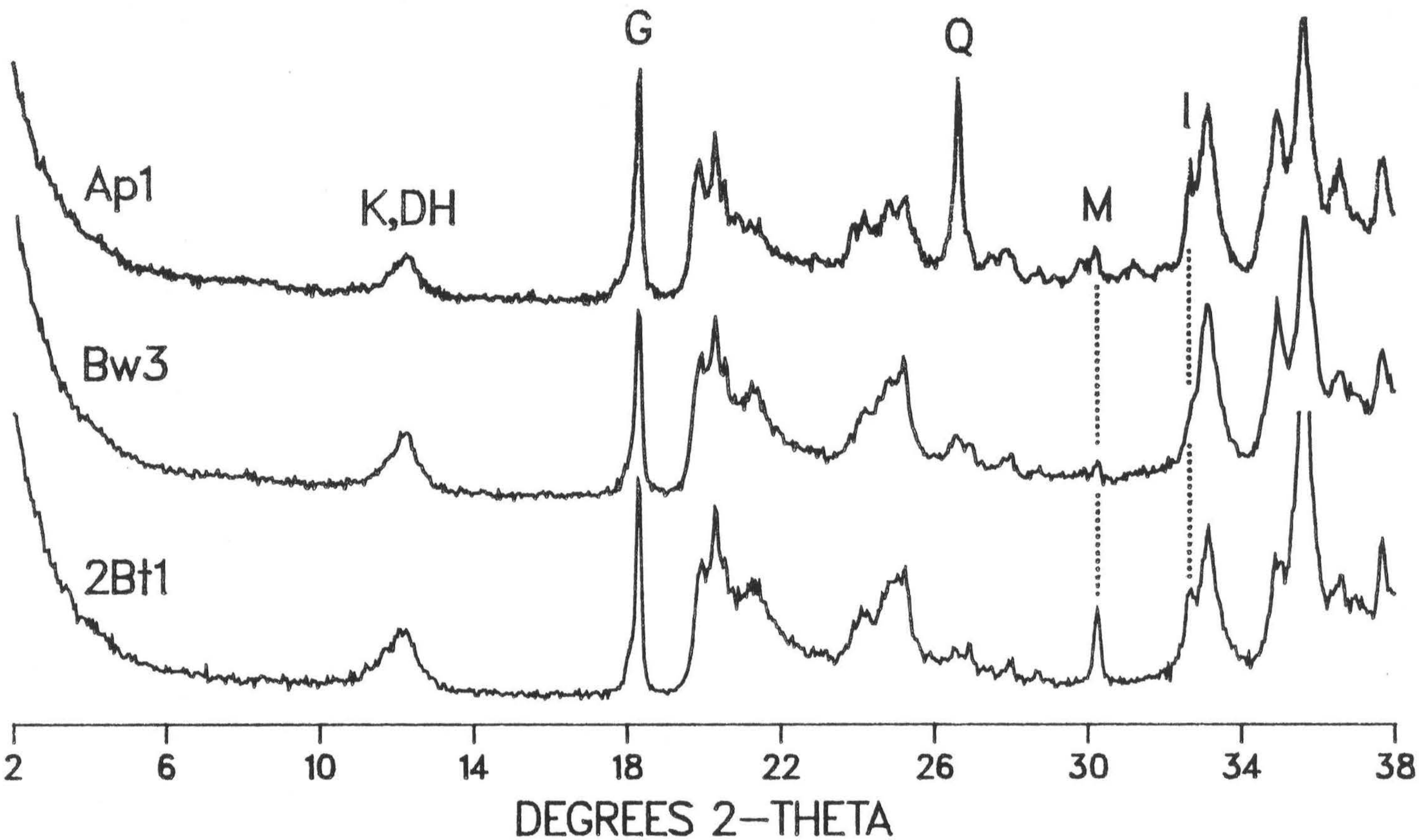

Figure 42. X-ray diffractograms of the Apl, Bw3, and 2Btl horizons of the Wahiawa series at Site 15. Magnetite and ilmenite peaks are indicated by the dotted lines.

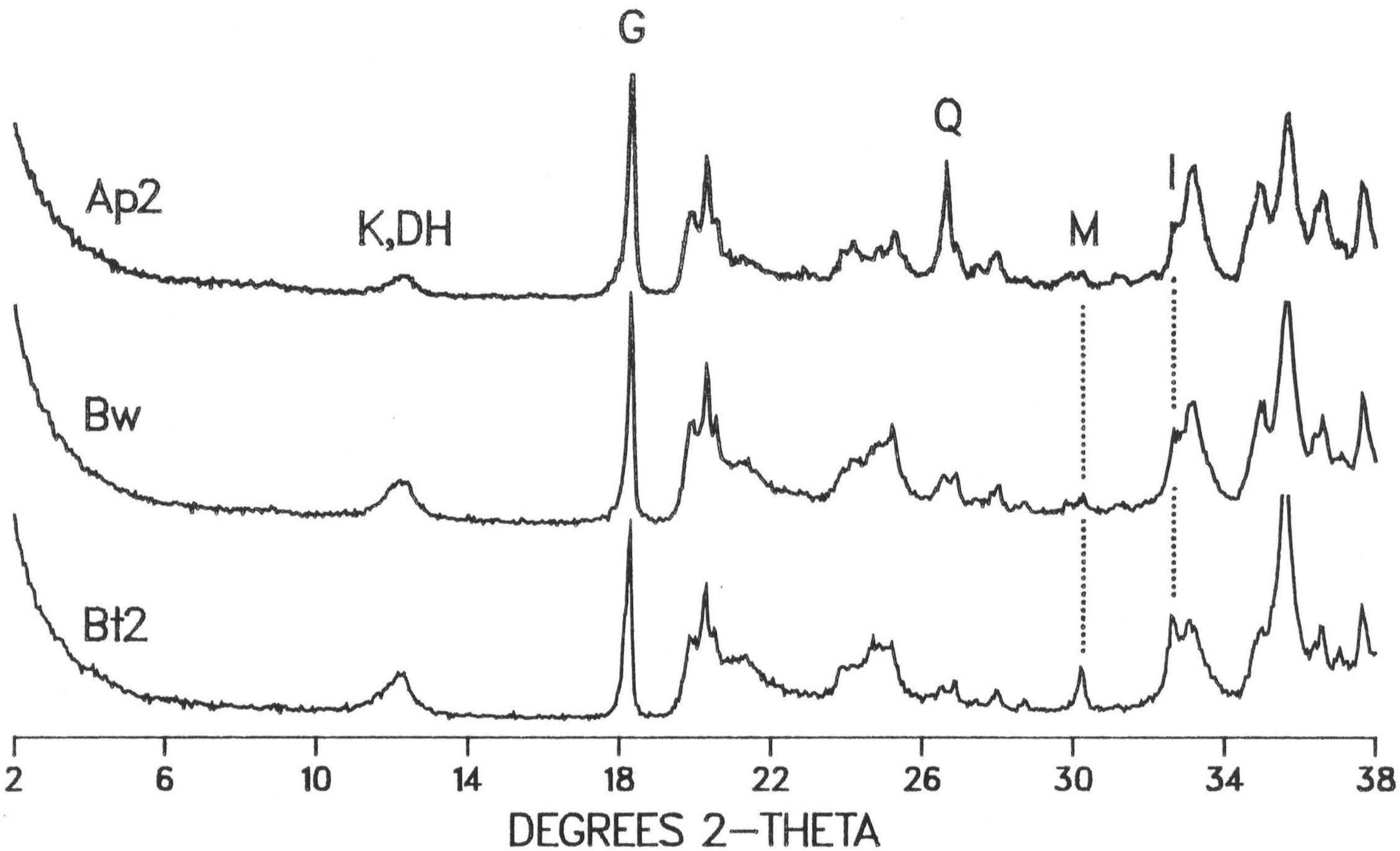

Figure 43. X-ray diffractograms of the Ap2, Bw, and Bt2 horizons of the Wahiawa series at Site 16. Magnetite and ilmenite peaks are indicated by the dotted lines.

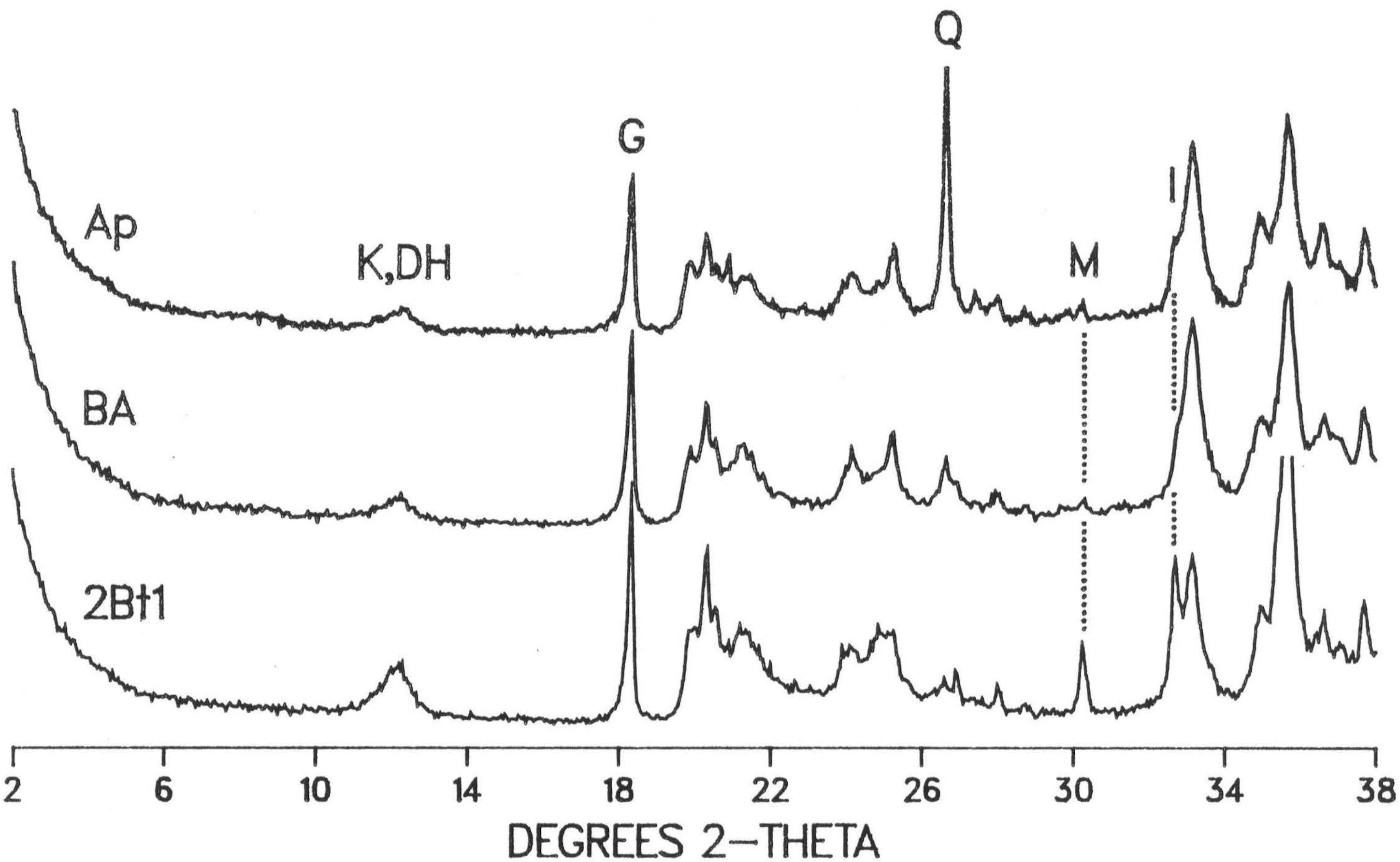

Figure 44. X-ray diffractograms of the Ap, BA, and 2Bt1 horizons of the Paaloa series at Site 17. Magnetite and ilmenite peaks are indicated by the dotted lines.

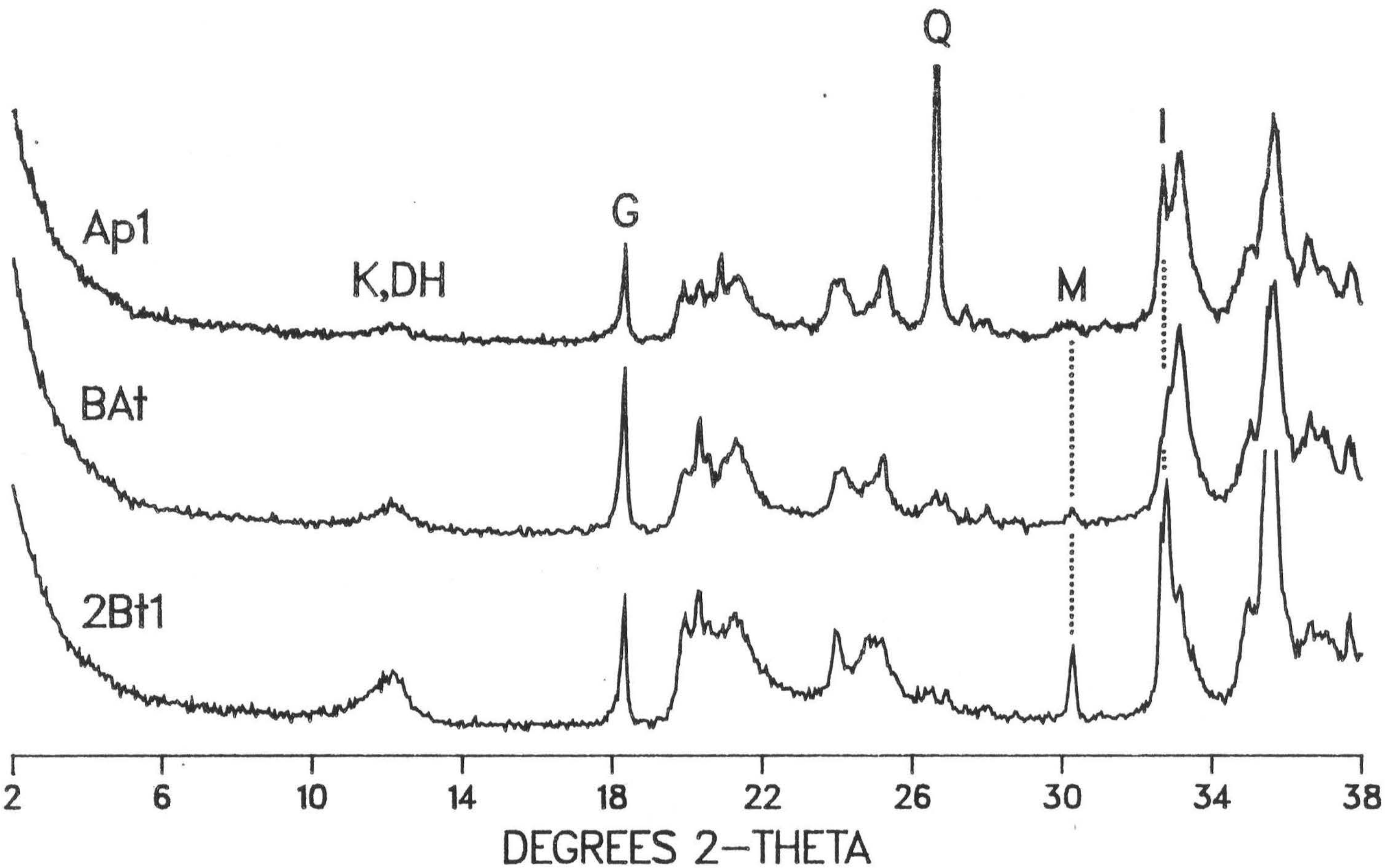

Figure 45. X-ray diffractograms of the Apl, BAt, and 2Btl horizons of the Paaloa series at Site 18. Magnetite and ilmenite peaks are indicated by the dotted lines.

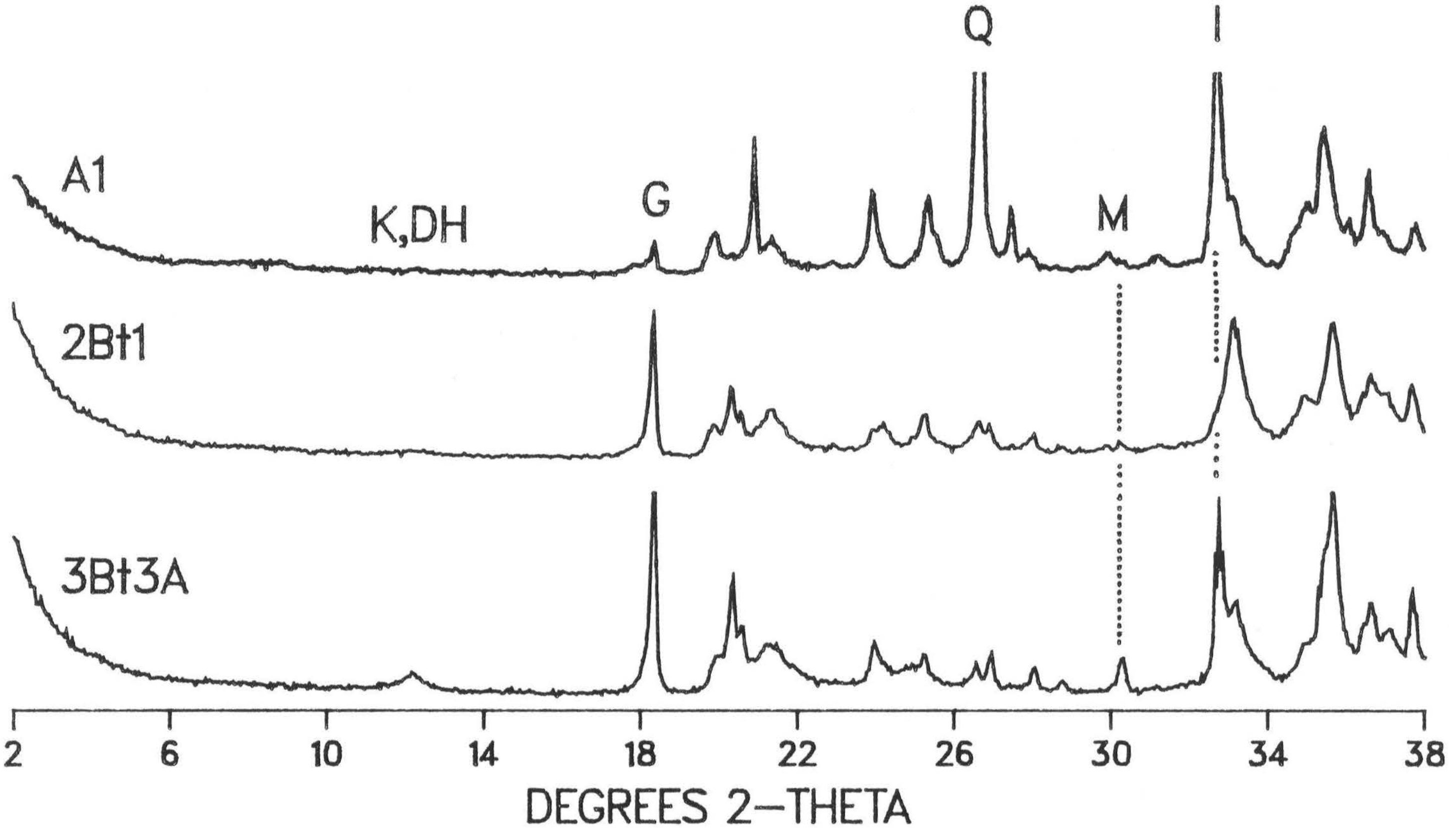

Figure 46. X-ray diffractograms of the A1, 2Bt1, and 3Bt3A horizons of the Paaloa series at Site 19. Magnetite and ilmenite peaks are indicated by the dotted lines.

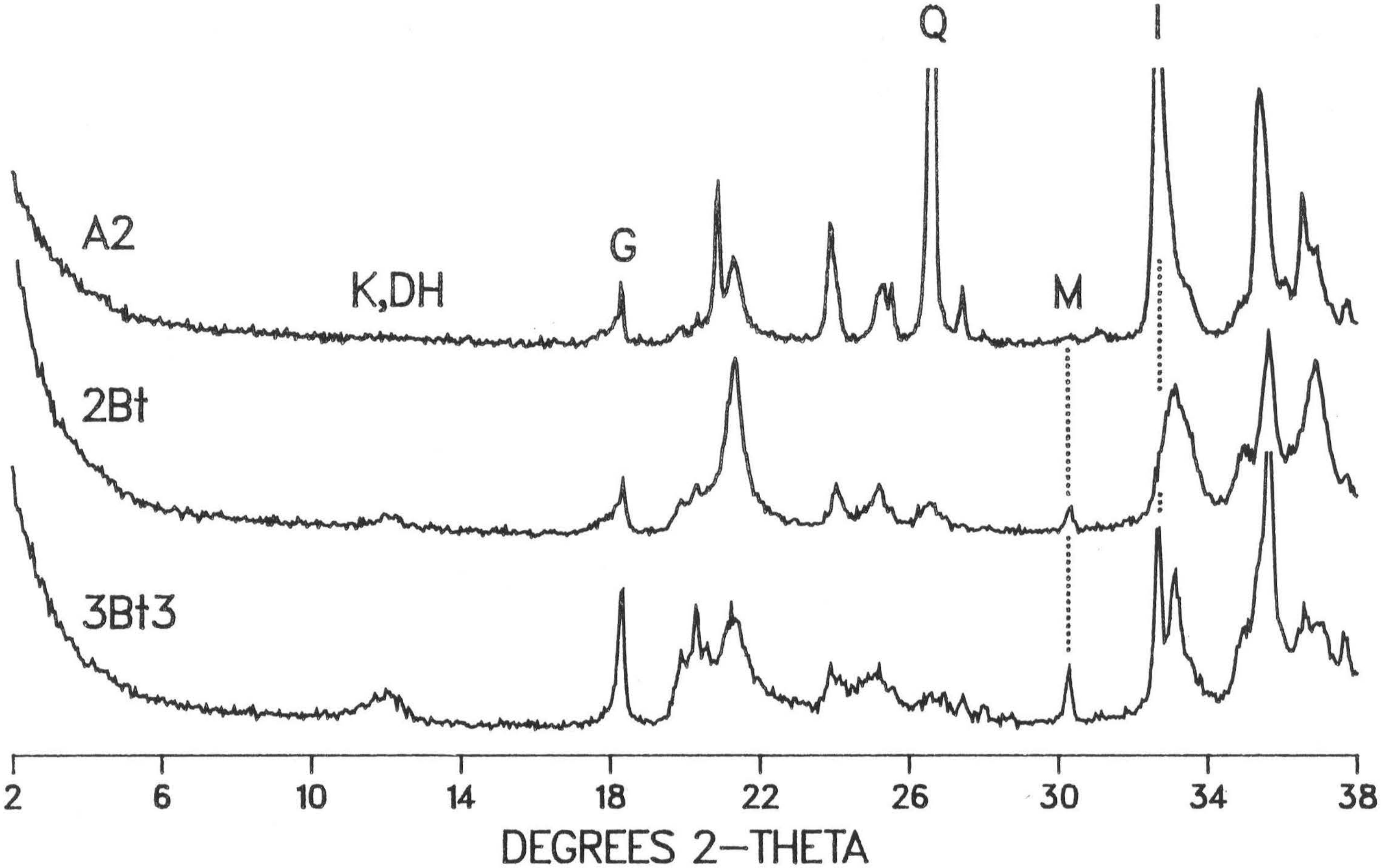

Figure 47. X-ray diffractograms of the A2, 2Bt, and 3Bt3 horizons of the Paaloa series at Site 20. Magnetite and ilmenite peaks are indicated by the dotted lines.

Appendix F. Correspondence from Dr. Stoops

Note: The Bt4 horizon in this correspondence should read 2Bt4 horizon.

RIJKSUNIVERSITEIT - GENT
INTER UTRUMQUE

LABORATORIUM voor MINERALOGIE, PETROGRAFIE en MICROPEDOLOGIE

Dir. : Prof. Dr. G. STOOPS
Dr. S. GEETS
Dr. R. NIJS

B-9000 GENT, 17 december 1987
Geologisch Instituut
Krijgslaan 281, S8
Tel. 091/22.57.15

194

Uitbr. : 2654

Uw ref. :
O. ref. : GST/242/87

Dr. I. IKAWA
University of Hawaii at Manoa
College of Tropical Agriculture and
Human Resources
Department of Agronomy and Soil Science
1910 East-West Road
Honolulu, Hawaii 96822

Dear Dr. Ikawa,

Enclosed I'm sending you the short description of the slides I made of the samples you sent me of the Molokai and Manana series. Next month I shall send you also some color slides illustrating the mean micromorphological characteristics; I had not yet the time to make them.

I would appreciate if you could send me later some information concerning these profiles for my own interest (e.g. the excursion guide).

Sincerely yours,

Prof. Dr. G. STOOPS.

Encl.: micromorphological descriptions

MICROMORPHOLOGICAL DESCRIPTION OF SOILS FROM HAWAII

G. STOOPS

I.MOLOKAI SERIES: TORROX

horizon (6 - 74 cm)(17.530)
Microstructure:irregular vughy (300 um) and channel (500 - 1000 um) microstructure superposed to locally more or less compacted granular microstructure composed of micropeds of medium to fine sand size, subangular to rounded, separated by triangular packing pores.
Groundmass
Coarse material (>5um): transparent minerals practically absent: irregular, angular to subangular opaque grains of 10 - 20 um in diameter.
Micromass: reddish brown, speckled and cloudy clay with undifferentiated b-fabric; reddish with incident light.
C/f ratio: 2/100.
C/f related distribution: open porphyric.
Pedofeatures
Rounded impregnative soil nodules with irregular linear impregnations of opaque (Mn ?) substances,sometimes concentric; 900 -1000 um in diameter. Probably desintegrating.
Loose discontinuous channel infillings with irregular rounded excrements.

horizon (76 - 84 cm) (17.531)
Microstructure: as above
Groundmass: as above, but some grains of iddingsite of medium sand size occur.
Pedofeatures:Concentric Mn- nodules. 500 um in diameter.Rounded, Mn-impregnated nodules, as above. One has a more saprolitic (?) content, including some grains of iddingsite. Total of nodules up to 15%

horizon (86 - 94cm) (17.532)
Microstructure: as above, although compacted zones of welded micropeds become larger.
Groundmass: as above, but more iddingsite.
Pedofeatures: as above.

horizon (102 - 109 cm) (17.533)
Microstructure: irregular subangular blocky peds (2.5 mm), moderatel devel loped, with intrapedal channel microstructure. and concave triangular pores resulting from the packing of the micropeds. Some zones have a micropedstructure as above.
Groundmass: as above, but opaque grains and iddingsite have increases to 10 %.
Pedofeatures: as above, but only 2% of nodules.

horizon (109 - 117 cm) (17.534)
As above

horizon (117 - 124 cm) (17.535)
Microstructure: not observed as sample was fragmented.
Groundmass: as above.
Pedofeatures: as above. Presence of one rounded, sand sized (500 um in diameter) weathered basalt fragment.

Comments

The soil has all micromorphological characteristics recognized in well drained Oxisols. namely a granular (or microped) structure, absence of weatherable minerals in the coarse fraction, an undifferentiated b-fabric and the absense of clay coatings. Coarse material is restricted to a few percent, and clearly points to a volcanic, probably basaltic parent material (presence of iddingsite). The iron oxyhydrate nodules in the upper part of the profile seems to be inherited.

It is interesting that the micromorphology does not show differences between this Torrox and other well drained Oxisols of the humid tropics.

II.MANANA SERIES: ORTHOXIC TROPOHUMULT

Ap1 horizon (0 - 12 cm) (18.504)
Heterogeneous mixture of reddish brown and different types of brown material.
Microstructure: complex: granular, crumby and subangular blocky with intrapedal channel structure.
Groundmass
1 Red aggregates (angular to subangular.coarse sand size)
Coarse material: practically absent; only few silt sized opaque grains, a few iddingsite fragments;
Micromass: homogeneous cloudy reddish clay, compact, with weakly striated b-fabric (e.g. circular striated);
C/f related distribution: open porphyric.
2 Brown aggregates (coarse sand size)
Coarse material: few, mainly silt sized opaque grains and few iddingsite fragments.
Micromass: dotted brownish clay with small intrapedal vughs; weakly speckled to undifferentiated b-fabric.
C/f related distribution: open porphyric
Pedofeatures: some aggregates contain small (100 um) nodules of the red material mentioned above.
3 Yellowish brown aggregates, subangular. coarse sand size.
Coarse material: few silt sized opaque and iddingsite grains.
Micromass: speckled yellowish brown clay, undifferentiated b-fabric.
C/f related distribution: open porphyric.
The brown material sometimes also act as a binding substance between the red aggregates.Some isolated fragments of weathered basalt (isotropic material) occur, even as some living roots.

Ap2 horizon (12 - 30 cm) (18.505).
Heterogeneous mixture of reddish brown and different types of brown material, as above.

Bt1 horizon (30 - 47 cm) (18.506)
Microstructure: channel structure superposed to granular (microped) and welded granular microstructure. The granular structure is especially clear in channel infillings.
Groundmass
Coarse material (> 5um): few iddingsite (fine to medium sand) and opaque (fine sand to silt) grains. Less than 5%.
Micromass: finely speckled reddish clay with undifferentiated b-fabric.
C/f related distribution: open porphyric.
Pedofeatures: few rounded nodules of more limpid reddish groundmass with striated b-fabric. and also of more brownish material containing limpid clay coatings and gibbsite linings as in Bt3; very rare nodules of microcrystalline gibbsite (medium sand size).

Bt2 horizon (47 - 65 cm) (18.507).
As above, except for more inclusions of the more brownish speckled material with undifferentiated b-fabric, containing probably phantoms of weathered minerals (are these inclusions weathered ash fragments?); their boundary is generally diffuse; they are of coarse sand size.
Few limpid reddish clay coatings and fragments of them, with strong orientation.

Bt2 horizon (65 - 82 cm) (18.508)
Microstructure: vughy and channel structure superposed locally to microped structure (fine sand size).
Groundmass
Coarse material: as above, but few volcanic rock fragments totally weathered to isotropic material.
Micromass: weakly speckled reddish clay, with weakly expressed circular striated and undifferentiated b-fabric in the microped zones; weak random striated in the more compact zones.
C/f related distribution: open porphyric.
Pedofeatures: few fragments of strongly oriented limpid red clay coatings.

Bt3 horizon (82 - 91 cm) (18.509).
Mixture of reddish material as above, with about 50 % of nodules (mediumto coarse sand size) of brownish material. and some rock fragments (medium to coarse sand size) weathered to isotropic substances and hematite.
Brownish material:
Microstructure: vughy and fissured.
Groundmass
Coarse material: 10 % of iddingsite and opaque grains: fine sand size: traces of weathered minerals.

C/f related distribution: open porphyric.
Pedofeatures: fine coatings of yellowish brown speckled clay and of reddish brown speckled clay. Both have a low birefringence. Rare very thin coatings of microcrystalline gibbsite, superposed to the clay coatings.

Bt4 horizon (91 - 120 cm) (18.510)
Same as above, but very heterogeneous brown material much richer in clay coatings, and more gibbsite lining these coatings. Also more weathered rock fragments.

Bt4 horizon (120 - 150 cm) (18.511)
Two types of material are present:
Heterogeneous brownish material:
Microstructure:angular blocky and channel microstructure.
Groundmass:
Coarse material: much fine sand and silt sized opaques:many rounded fragments of different types of volcanic rocks, completely weathered to isotropic material: fragments of iddingsite and olivine pseudomorphs.
Micromass: brown to brownish red, dotted, woith undifferentiated b-fabric.
Pedogfeatures: abundant, thick, rather homogeneous coatings of orange clay on channels and interpedal voids: freqently covered by thin coatings of microcrystalline gibbsite.

Homogeneous brownish material:
Microstructure: intrapedal channel and (lobated) vugh structure?.
Groundmass
Coarse material: fine sand and silt sized opaque grains and iddingsite fragments.
Micromass: brown, speckled to dotted, undifferentiated b-fabric.
Pedofeatures: many coatings on vughs, composed of coarse clay, but also limpid yellowish red coatings: in some pores also illuviation of reddish clay from overlying horizons.

2BCt horizon (150 - 170 cm) (18.512)
As above.

2BCt horizon (175 - 205 cm) (18.513 cm).
Microstructure: complex: angular blocky and channel structure; locally granular.
Groundmass
Coarse material: fine sand and silt sized opaque grains, iddingsite grains; rounded, medium sand sized fragments of in situ weathered basalt; rare palagonite fragments?
Micromass: cloudy, speckled reddish brown clay with undifferentiated b-fabric.
Pedofeatures: coatings and infillings of coarse, weakly oriented clay; also few coatings of limpid, strongly oriented clay.

Comments

The Ap horizon seems to be a mixture of different materials, caused by repeated plowing, and vertical translocation of material from deeper horieons (e.g. by biological activity). supply of colluvial material however i!s not excluded.

The micromorphology of the Bt1 and Bt2 horizons corresponds to that of well developed kaolinitic red soils; the red colour and the absence of weatherable minerals indicates a high degree of weathering; the microped structure is the same as that observed in many well drained Oxisols; it seems especially related to biopores. The weak or undifferentiated b-fabric is characteristic both for oxic materials and for well drained soils developed on volcanic ash. Evidences of clay illuviation are present, but scarse.

The Bt3 seems a transitional horizon between Bt2 and Bt4, and overlaps probably a lithological discontinuity. The Bt4 itselfs seems to be a partially homogenised material of the same composition as found in the 2BCt, which clearly shows weathering pseudomorphs of volcanic rocks and olivine.

Based only on micromorphological evidences, without any knowledge of the field or analyticalata, it is not possible to explain this alternation of layers. Following hypothesis could be prudently proposed: the soil is polygenetic, consisting of a lower part (2BCt and Bt4), being the rests of a truncated soil, covered by a more developed and homogenised soil material (Ap, Bt1 and Bt2). The latter material could be the result of the colluvionation of an already kaolinitic soils. This could explain the heterogeneous composition of the transition zone.

Description were made according to the terminology of the "Handbook for Soil Thin Section Description", 1985, by Bullock, P., Federoff, N., Jongerius, A., Stoops, G. and Tursina, T.
!

RIJKSUNIVERSITEIT - GENT

LABORATORIUM voor
MINERALOGIE, PETROGRAFIE
en MICROPEDOLOGIE

Dir. : Prof. Dr. G. STOOPS
Dr. S. GEETS
Dr. R. NIJS

B-9000 GENT, 21 januari 1988
Geologisch Instituut
Krijgslaan 281, S8
Tel. 091/22.57.15

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Uitbr. : 2654

Uw ref. :
O. ref. : GST/16/88

Dr. H. IKAWA
University of Hawaii at Manoa
College of Tropical Agriculture and Human Resources
Department of Agronomy and Soil Science
1910 East-West Road
Honolulu, Hawaii 96822

Dear Dr. Ikawa,

Enclosed I'm sending you some micrographs illustrating the most characteristic features of the two profiles from Hawaii I described. The magnification indicated refers to the real magnification measured on the slide. If you make diaprints of these, you have of course to recalculate the magnification.

Enclosed also a new version of the discussion of the ultisols; the one that was forwarded was not complete, as the discussion of the, rather important gibbsite coatings was missing.

Sincerely yours,

Prof. Dr. G. STOOPS.

The Ap horizon seems to be a mixture of different materials, caused by repeated plowing, and vertical translocation of material from deeper horieons (e.g. by biological activity). supply of colluvial material however is not excluded.

The micromorphology of the Bt1 and Bt2 horizons corresponds to that of well developed kaolinitic red soils: the red colour and the absence of weatherable minerals indicates a high degree of weathering; the microped structure is the same as that observed in many well drained Oxisols; it seems especially related to biopores. The weak or undifferentiated b-fabric is characteristic both for oxic materials and for well drained soils developed on volcanic ash. Evidences of clay illuviation are present, but scarse.

The Bt3 seems a transitional horizon between Bt2 and Bt4, and overlaps probably a lithological discontinuity. The Bt4 itselfs seems to be a partially homogenised material of the same composition as found in the 2BCt, which clearly shows weathering pseudomorphs of volcanic rocks and olivine.

Based only on micromorphological evidences, without any knowledge of the field or analytical data, it is not possible to explain this alternation of layers. Following hypothesis could be prudently proposed: the soil is polygenetic, consisting of a lower part (2BCt and Bt4), being the rests of a truncated soil, covered by a more developed and homogenised soil material (Ap, Bt1 and Bt2). The latter material could be the result of the colluvionation of an already kaolinitic soils. This could explain the heterogeneous composition of the transition zone.

The presence of linings of microcrystalline gibbsite superposed to clay illuviation coatings in the Bt3 and especially in the Bt4 points also to a polygenetic origin. A mobilisation and transport of the Al (in ionic form?)took place after the deposition of the clay coatings, and is most probably the result of processes taking place in the superposed materials.

Description were made according to the terminology of the "Handbook for Soil Thin Section Description", 1985, by Bullock, P., Federoff, N., Jongerius, A., Stoops, G. and Tursina, T.

Appendix G. Classification of the soils of the study area.

Site	Series	Foote et al. (1972)	This study
2	Kolekole	fine, oxidic, isothermic Ustoxic Humitropepts	medial over clayey, isothermic Andeptic Haplohumults
3	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, mixed, isothermic Humic Rhodic Kandiustox
9	Manana	clayey, oxidic, isothermic Orthoxic Tropohumults	clayey, ferruginous, isothermic Humic Rhodic Kandiustox
10	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, mixed, isothermic Humic Rhodic Haplustox
11	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, mixed, isothermic Humic Rhodic Haplustox
12	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, mixed, isothermic Humic Rhodic Kandiustox
13	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, ferruginous, isothermic Humic Rhodic Haplustox
14	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, mixed, isothermic Humic Rhodic Haplustox
15	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, sesquic, isothermic Humic Rhodic Haplustox
16	Wahiawa	clayey, kaolinitic, isothermic Tropeptic Eutrustox	clayey, sesquic, isothermic Humic Rhodic Haplustox
17	Paaloa	clayey, oxidic, isothermic Humoxic Tropohumults	clayey, sesquic, isothermic Humic Rhodic Kandiudox
18	Paaloa	clayey, oxidic, isothermic Humoxic Tropohumults	clayey, ferruginous, isothermic Humic Kandiudox

19	Paaloa	clayey, oxidic, isothermic Humoxic Tropohumults	clayey, sesquic, isothermic Humic Kandiudox
20	Paaloa	clayey, oxidic, isothermic Humoxic Tropohumults	clayey, ferruginous, isothermic Humic Kandiudox

LITERATURE CITED

Arnold, R.W. 1968. Pedological significance of lithologic discontinuities. In: Trans. 9th Int.Congr.of Soil Sci. Adelaide, Australia. IV:595-603.

Arnold, R.W. 1979. Concept of the argillic horizon and problems of its identification. In: Proc. 2nd Int. Soil Classif. Workshop. Part II. Thailand. 3-9 Sept. 1978. pp.21-34.

Beinroth, F.H., G. Uehara, and H. Ikawa. 1974. Geomorphic relationships of Oxisols and Ultisols on Kauai, Hawaii. Soil Sci. Soc. Am. Proc. 38:128-31.

Birkeland, P.W. 1974. Pedology, weathering, and geomorphological research. Oxford Univ. Press: New York. 285p.

Blake, G.R. 1965. Bulk density. In: Methods of soil analysis, Part 1. C.A. Black et al. (eds.). Agronomy 9:374-390.

Blakemore, L.C., P.L. Searle, and B.K. Daly. 1987. Methods for chemical analysis of soils. New Zealand Soil Bureau Scientific Report 80.

Bricker, O. and J. Prospero. 1969. Airborne dust on the Bermuda Islands and Barbados. AGU Trans. 50:176.

Bryan, K. and C. Albritton, Jr. 1943. Soil phenomena as evidence of climatic changes. Am. J. Sci. 241:469-90.

Bryan, W. and L. Teakle. 1946. Pedogenic inertia - a concept in soil science. Nature 164:969.

Buol, S.W. 1979. Geomorphology of some Oxisols. In: Proc. of 2nd Int. Soil Classification Workshop. Part 1: Malaysia. 28 Aug - 1 Sept, 1978. pp.37-43. 345p.

Buol, S.W. 1986. LAC-Oxisol interface. In: Symposium on low activity clay (LAC) soils. Soil Mgmt. Support Services. Tech. Monograph no.14.

Buol, S.W., F.D. Hole, and R.J. McCracken. 1980. Soil Genesis and Classification. 2nd ed. Iowa St. Univ. Press: Ames, Iowa. 406p.

Chorley, R., S. Schumm, and D. Sugden. 1984. Geomorphology. NY: Methuen & Co. 604p.

Chuey, J., D. Rea, and N. Pisias. 1987. Late Pleistocene paleoclimatology of the central equitorial Pacific: a quantitative record of eolian and carbonate deposition. Quat Res. 28:323-339.

Clague, D. and F. Frey. 1982. Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: implications for the ocean mantle below Hawaii. J. Petrology 23:447-504.

Clayton, R.N., R.W. Rex, J.K. Syers, and M.L. Jackson. 1972. Oxygen isotope abundance in quartz from Pacific pelagic sediments. J. Geophys. Res. 77:3907-3915.

Cline, M.G. 1955. Soils and climate. In: Soil survey, Territory of Hawaii. USDA. Soil survey series 1939. no.25 pp.89-95.

Daniels, R.B., E.E. Gamble, and J.G. Cady. 1971. The relation between geomorphology and soil morphology and genesis. Adv. in Agronomy. 23:51-87.

de Villiers, J. 1965. Present soil forming factors and processes in tropical and subtropical regions. Soil Sci. 99:50-57.

Doell, R.R. and G.B. Dalrymple. 1973. Potassium-argon ages and paleomagnetism of the Waianae and Koolau Volcanic Series, Oahu, Hawaii. Geol. Soc. Am. Bull. 84:1217-42.

Donn, W.L., W.R. Farrand, and M. Ewing. 1962. Pleistocene ice volumes and sea level lowering. J. Geol. 70:206-14.

Dudal, R. and M. Soepraptohardjo. 1960. Some considera-tions on the genetic relationships between Latosols and Andosols in Java (Indonesia). Trans. 7th Int. Congr. Soil Sci., Madison, Wisc., USA. V:229-237.

Dymond, J., P. Biscaye, and R. Rex. 1974. Eolian origin of mica in Hawaiian soils. Geol. Soc. Amer. Bull. 85:37-40.

Eswaran, H. 1981. Alfisols and Ultisols. In: Proc. of South Pacific Regional Forum on Soil Taxonomy, Suva Fiji. 2-13 Nov., 1981. pp.115-27. Morrison, R.J. and D.M. Leslie (eds.). Inst. Nat. Res., Univ. South Pacific. Suva, Fiji. 445p.

Eswaran, H. and F. De Coninck. 1971. Clay mineral transformation in basaltic soils in tropical environments. Pedologie 21:181-210.

Eswaran, H. and C. Sys. 1979. Argillic horizon in LAC soils. Formation and significance to classification. Pedologie 29:175-90.

Eswaran, H. and R. Tavernier. 1980. Classification and genesis of Oxisols. In: Soils with variable charge. pp.427-42. Theng, B.K.G. (ed.). Offset Publ.: Palmerston North, New Zealand. 448p.

Finkl, C.W., Jr. 1980. Stratigraphic principles and practices as related to soil mantles. Catena 7:195-204.

Flint, R.F. 1971. Glacial and Quaternary Geology. New York: J. Wiley and Sons. 892p.

Foote, D., E. Hill, S. Nakamura, and F. Stephens. 1972. Soil survey of the islands of Kauai, Oahu, Maui, Molokai, and Lanai. State of Hawaii. USDA, SCS. Washington, D.C. U.S. Govt. Printing Office. 232p.

Funkhouser, J.G. 1968. The determination of a series of ages of Hawaiian volcanoes by potassium-argon method. Pacific Sci. 22:369-72.

Giambelluca, T., M. Nullet, and T. Schroeder. 1986. Rainfall Atlas of Hawai'i. Report R76. State of Hawaii. Dept. of Land and Natural Resources. Honolulu, Hawaii.

Goldberg, E.D., and M. Koide. 1962. Geochronological studies of deep sea sediments by the ionium/titanium method. Geochim. Acta 26:417-450.

Gramlich, J.W., V.A. Lewis, and J.J. Naughton. 1971. Potassium-argon dating of Holocene basalts of the Honolulu Volcanic Series. Geol. Soc. Am. Bull. 82:1399-1404.

Hall, G. 1983. Pedology and geomorphology. In: Pedogenesis and soil taxonomy. I. Concepts and interactions. Wilding, L. N. Smeck, and G. Hall (eds.). pp. 117-140.

Hay, R. and A. Iijima. 1968. Nature and origin of palogonite tuffs of the Honolulu Group on Oahu, Hawaii. In: Studies in Volcanology. Coats, R., R. Hay, and C. Anderson. GSA Memoir 116:331-76.

Herbillion, A.J. 1980. Mineralogy of Oxisols and oxic materials. In: Soils with variable charge. pp.109-26. Theng, B.K.G. (ed.). Offset Publ.: Palmerston North, New Zealand. 448p.

Hough,G.J. and P.L. Gile. 1941. Rock weathering and soil profile development in the Hawaiian Islands. USDA Tech. Bull. no.752. 43p.

Hudnall, W.H. 1977. Genesis and morphology of secondary products in selected volcanic ash soils from the Island of Hawaii. Ph.D. dissertation, Univ. of Hawaii.

Hunt, C.B. 1972. Geology of soils. W.H. Freeman and Co.: San Francisco. 344p.

Isbell, R.F. 1980. Genesis and classification of low activity clay Alfisols and Ultisols. In: Soils with variable charge. pp.397-410. Theng, B.K.G. (ed.). Offset Publ.: Palmerston North, New Zealand. 448p.

Jackson, M.L. 1956. Soil chemical analysis - advanced course. Published by the author, Dept. of Soils, Univ. of Wisconsin, Madison, Wisconsin.

Jackson, M.L., T.W.M. Levelt, J.K. Syers, R.W. Rex, R.N. Clayton, G.D. Sherman, and G. Uehara. 1971. Geomorphological relationships of tropospherically derived quartz in the soils of the Hawaiian Islands. Soil Sci. Soc. Am. Proc. 35: 515-25.

Janecek, T. and D. Rea. 1985. Quaternary fluctuations in the northern hemisphere trade winds and westerlies. Quat. Res. 24:150-163.

Jones, R.C. 1989. A computer technique for x-ray diffraction curve fitting/peak decomposition. Chapter in Spec. Publ. of the Clay Minerals Society. In press.

Jones, R.C., W.H. Hudnall, and W.S. Sakai. 1982. Some highly weathered soils of Puerto Rico, 2. Mineralogy. Geoderma 27:75-137.

Jones, S. and R. Bellaire. 1937. The classification of Hawaiian climates. A comparison of the Koppen and Thornthwaite systems. Geog. Rev. 27:112-119.

Kanehiro, Y. 1987. personal communication.

Kilmer, V.J. and L.T. Alexander. 1949. Methods of making mechanical analyses of soils. Soil Sci. 68:15-24.

Lamphere, M.A. and G.B. Dalrymple. 1980. Age and strontium isotopic composition of the Honolulu Volcanic Series, Oahu, Hawaii. Am. J. Sci. 280-A:736-51.

Leopold, L. 1951. Hawaiian climate - its relation to human and plant geography. Meteorol. Mon. 1:1-6.

Lepsch, I., S. Buol, and R. Daniels. 1977a. Soil-landscape relationships in the Occidental Plateau of Sao Paulo State, Brazil. I. Geomorphic surfaces and mapping units. Soil Sci. Soc. Am. J. 41:104-09.

Lepsch, I., S. Buol, and R. Daniels. 1977b. Soil-landscape relationships in the Occidental Plateau of Sao Paulo State, Brazil. II. Soil morphology, genesis, and classification. Soil Sci. Soc. Am. J. 41:109-14.

Macdonald, G.A. 1940. Petrography of the Waianae Range, Oahu. In: Stearns, H.T. Supplement to geology and ground-water resources of the Island of Oahu, Hawaii. Hawaii Div. of Hydrography, Bull. 5:61-91.

Macdonald, G.A. and T. Katsura. 1964. Chemical composition of Hawaiian lavas. J. Petrology 5:82-133.

Macdonald, G.A., A.T. Abbott, and F.L. Peterson. 1983. Volcanoes in the sea. 2nd ed. Honolulu: Univ. Hawaii Press. 517p.

Macnish, S., A. Koppi, I. Little, and B. Schafer. 1987. The distribution, nature and origin os some red sesquioxidic materials in southeastern Queensland, Australia. Geoderma 41:1-27.

McDougall, I. 1964. Potassium-argon ages from lavas of the Hawaiian Islands. Geol. Soc. Am. Bull. 75:107-28.

McKeague, J.A. and J.H. Day. 1966. Dithionite- and oxalate-extractable iron and aluminum as aids in differentiating various classes of soils. Can. J. Soil Sci. 46:13-22.

McLean, E. 1982. Soil pH and lime requirement. In: Methods of soil analysis, Part 2. 2nd ed. A.L. Page et al. (eds.). Agronomy 9:199-224.

McLean, E.O. 1965. Aluminum. In: Methods of soil analysis, Part 2. C.A. Black et al. (eds.). Agronomy 9:978-998.

Miller, B.J. 1983. Ultisols. In: Pedogenesis and Soil Taxonomy. II. The soil orders. pp.283-323. Wilding, L.P., N.E. Smeck, and G.F. Hall (eds.). Amsterdam: Elsevier Science Publ. 410p.

Modensi, M.C. 1983. Weathering and morphogenesis in a tropical plateau. Catena 10:237-251.

Molina-Cruz, A. 1977. The relation of the southern trade winds to upwelling processes during the last 75,000 years. Quat. Res. 8:324-38.

Moniz, A. and S. Buol. 1982. Formation of an Oxisol- Ultisol transition in Sao Paulo, Brazil. I. Double-water flow model of soil development. Soil Sci. Soc. Am. J. 46:1228-33.

Montagne, H. 1970. Crust development in a Titaniferous Ferruginous Latosol on Kauai, Hawaii. M.S. Thesis, Univ. of Hawaii.

Moore, J. and G. Moore. 1984. Deposit from a giant wave on the island of Lanai, Hawaii. Science 226:1312-15.

Moorman, F.R. and A. Van Wambeke. 1978. The soils of the lowland rainy tropical climates: their inherent limitations for food production and related climatic constraints. 11th Int. Cong. Soil Sci. vol. 2. Plenary session papers. Edmonton, Alberta, Canada. June 19-27, 1978. pp. 272-91. 359p.

Naidu, R., J. Kirkman, and R. Morrison. 1987. Mineralogy of soils from basaltic ash, Taveuni, Fiji. Geoderma 39:181-92.

Nikiforoff, C.C. 1953. Pedogenic criteria of climatic changes. In: Climatic changes. Shapley, H. (ed.). pp.189-200. Harvard Univ. Press: Cambridge. 318p.

Oertel, A.C. and J.B. Giles. 1966. Quantitative study of a layered soil. Aust. J. Soil Res. 4:19-28.

Palmer, H.S. 1955. Geomorphic contrasts within the Koolau Range of Oahu, Hawaii. Pacific Sci. 9:304-17.

Porter, S.C. 1979 Hawaiian glacial ages. Quat. Res. 12: 161-87.

Price, S. 1983. Climate. In: Atlas of Hawaii. 2nd ed. pp.59-66. R.W. Armstrong (ed.). Honolulu: Univ. of Hawaii Press.

Rex, R.W., J.K. Syers, M.L. Jackson, and R.N. Clayton. 1969. Eolian origin of quartz in soils of the Hawaiian Islands and in Pacific pelagic sediments. Science 163:277-279.

Richards, L.A. 1965. Physical condition of water in soil. In: Methods of soil analysis, Part 2. C.A. Black et al. (eds). Agronomy 9:128-152.

Roden, M., F. Frey, and D. Clague. 1984. Geochemistry of tholeiitic and alkalic lavas from the Koolau Range, Oahu, Hawaii: implications for Hawaiian volcanism. Earth and Planet. Sci. Letters 69:141-158.

Ruhe, R.V. 1960. Observations in Hawaii. Jan. 17-29,1960. unpublished field notes.

Ruhe, R.V. 1961. Observations in Hawaii II. March 11-26, 1961. unpublished field notes.

Ruhe, R.V. 1964. An estimate of paleoclimate in Oahu, Hawaii. Am. J. Sci. 262: 1098-1115.

Ruhe, R.V. 1965. Relation of fluctuations of sea level to soil genesis in the Quaternary. Soil Sci. 99: 23-29.

Ruhe, R.V. 1969. Principles for dating pedogenic events in the Quaternary. Soil Sci. 107:398-401.

Ruhe, R.V. 1975. Geomorphology. Boston: Houghton Mifflin Co. 246p.

Ruhe, R.V. and R.B. Daniels. 1958. Soils, paleosols, and soil-horizon nomenclature. Soil Sci. Soc. Am. Proc. 22:66-69.

Ruhe, R.V., J.M. Williams, and E.L. Hill. 1965a. Shorelines and submarine shelves, Oahu, Hawaii. J. Geol. 73: 485-97.

Ruhe, R.V., J.M. Williams, R.C. Shuman, and E.L. Hill. 1965b. Nature of soil parent material in Ewa-Waipahu area, Oahu, Hawaii. Soil Sci. Soc. Am. Proc. 29: 282-87.

Selling, O.H. 1948. Studies in Hawaiian pollen statistics. Part III. On the late Quaternary history of the Hawaiian vegetation. Bishop Mus. Spec. Pub. 39. Honolulu.

Sherman, G.D. 1949. Factors influencing the development of lateritic and laterite soils in the Hawaiian Islands. Pacific Sci. 3:307-14.

Sherman, G.D., Z.C. Foster, and C.K. Fujimoto. 1948. Some properties of the Ferruginous Humic Latosols of the Hawaiian Islands. Soil Sci. Soc. Am. Proc. 13:471-76.

Sherman, G.D. and L.T. Alexander. 1959. Characteristics and genesis of Low Humic Latosols. Soil Sci. Soc. Am. Proc. 23:168-70.

Sinton, J. 1986. Revision of stratigraphic nomenclature of Waianae Volcano, Oahu, Hawaii. U.S. Geol. Surv. Bull. 1775-A:9-15.

Soil Conservation Service. 1972. Soil survey laboratory methods and procedures for collecting soil samples. Soil Survey Investigations Report No. 1.

Soil Conservation Service. 1984. Glossary of selected geomorphic terms for western soil surveys. West Nat. Tech. Cntr. Portland, Oregon.

Soil Survey Staff. 1975. Soil Taxonomy. U.S. Dept. Agr. Handbook 18. 503p.

Soil Survey Staff. 1987. Keys to Soil Taxonomy. SMSS Tech. Mono. no.6. Ithaca, NY.

Stearns, H.T. 1935. Pleistocene shorelines on the islands of Oahu and Maui, Hawaii. GSA Bull. 46:1927-56.

Stearns, H.T. 1974. Correlation of Pleistocene shorelines in Gippsland, Australia, and Oahu, Hawaii: Discussion. GSA Bull. 86:1189.

Stearns, H.T. 1978. Quaternary shorelines in the Hawaiian Islands. Bishop Mus. Bull. 237. Honolulu.

Stearns, H.T. and K.N. Vaksvik. 1935. Geology and groundwater resources of the island of Oahu, Hawaii. Hawaii Div. Hydrography. Bull. 1.

Stoops, G. 1988. personal communication.

Swindale, L. and G. Uehara. 1966. Ionic relationships in the pedogenesis of Hawaiian soils. Soil Sci. Soc. Am. Proc. 30:726-730.

Tanada, T. 1951. Certain properties of the inorganic colloidal fraction of Hawaiian soils. J. Soil Sci. 2:83-96.

Tamura, T., M.L. Jackson, and G.D. Sherman. 1953. Mineral content of Low Humic, Humic, and Hydrol Humic Latosols of Hawaii. Soil Sci. Soc. Am. Proc. 17:343-46.

Thomas, G.W. 1982. Exchangeable cations. In: Methods of soil analysis, Part 2. 2nd ed. A.L. Page et al. (eds.). Agronomy 9:159-166.

U.S. Dept. of Agriculture. 1962. aerial photos EKM-1CC-95, 96, 97, 98, 99, 118, 119, 141, 142. Agricultural Research Service.

U.S. Dept. of Agriculture. 1976. Soil survey laboratory data and descriptions for some soils of Hawaii. Soil Conservation Service. Soil survey investigations report no.29. 208p.

U.S. Geological Survey. 1977. aerial photos GS-VEEE 9-21, 22, 23 and 9-32, 33, 34. Dec. 13, 1977. Dept. of the Interior.

U.S. Geological Survey. 1953a. Hauula Quadrangle. 7.5 minute series topographic map.

U.S. Geological Survey. 1953b. Schofield Barracks Quadrangle. 7.5 minute series topographic map.

U.S. Geological Survey. 1960. Haleiwa Quadrangle. 7.5 minute series topographic map.

Van Wambeke, A., H. Eswaran, A. Herbillon, and J. Comerma. 1983. Oxisols. In: Pedogenesis and Soil Taxonomy. II. The soil orders. pp. 325-354. Wilding, L., N. Smeck, and G. Hall (eds.). NY:Elsevier. 410 p.

Wada, K. 1977. Allophane and imogolite. In: Minerals in soil envinonments. pp. 603-638. Dixon, J. and S. Weed (eds.). Madison:Soil Science Society of America. 948 p.

Wada, K. 1985. The distinctive properties of Andosols. Adv. in Soil Sci. 2:173-229.

Wada, K., T. Henmi, N. Yoshinaga, and S. Patterson. 1972. Imogolite and allophane formed in saprolite of basalt on Maui, Hawaii. Clays Clay Min. 20:375-380.

Wada, K. and S. Wada. 1976. Clay mineralogy of the B horizons of two Hydrandepts, a Torrox, and a Humitropept in Hawaii. Geoderma 16:139-157.

Walker, G.P.L. 1989. personal communication.

Walker, J.L., G.D. Sherman, and T. Katsura. 1969. The iron and titanium minerals in the Titaniferous Ferruginous Latosols of Hawaii. Pac. Sci. 23:291-304.

Wang, C. and R. Arnold. 1973. Quantifying pedogenesis for soils with discontinuities. Soil Sci. Soc. Am. Proc. 37:271-278.

Warkentin, B. and T. Maeda. 1980. Physical and mechanical characteristics of Andisols. In: Soils with variable charge. pp. 281-302. Theng, B.K.G. (ed.). Offset Publ.: Palmerston North, New Zealand. 448p.

Wentworth, C.K. 1926. Pyroclastic geology of Oahu. B.P. Bishop Mus. Bull. 30.

Wentworth, C.K. and H. Winchell. 1947. Koolau basalt series. Geol. Soc. Amer. Bull. 58:49-77.

Winchell, H. 1947. Honolulu Series, Oahu, Hawaii. Geol. Soc. Am. Bull. 58:1-48.

Windom, H.L. 1969. Atmospheric dust records in permanent snowfields: implications to marine sedimentation. Geol. Soc. Amer. Bull. 80:761-782.

Witty, J. 1988. personal communication.

Yeh, T., J. Carson, and J. Marciano. 1951. On the relation between the circumpolar westerly current and rainfall over the Hawaiian Islands. Meteorol. Mon. 1:47-55.

Yeh,T., C. Wallen, and J. Carson. 1951. A study of rainfall over Oahu. Meteorol. Mon. 1:34-46.

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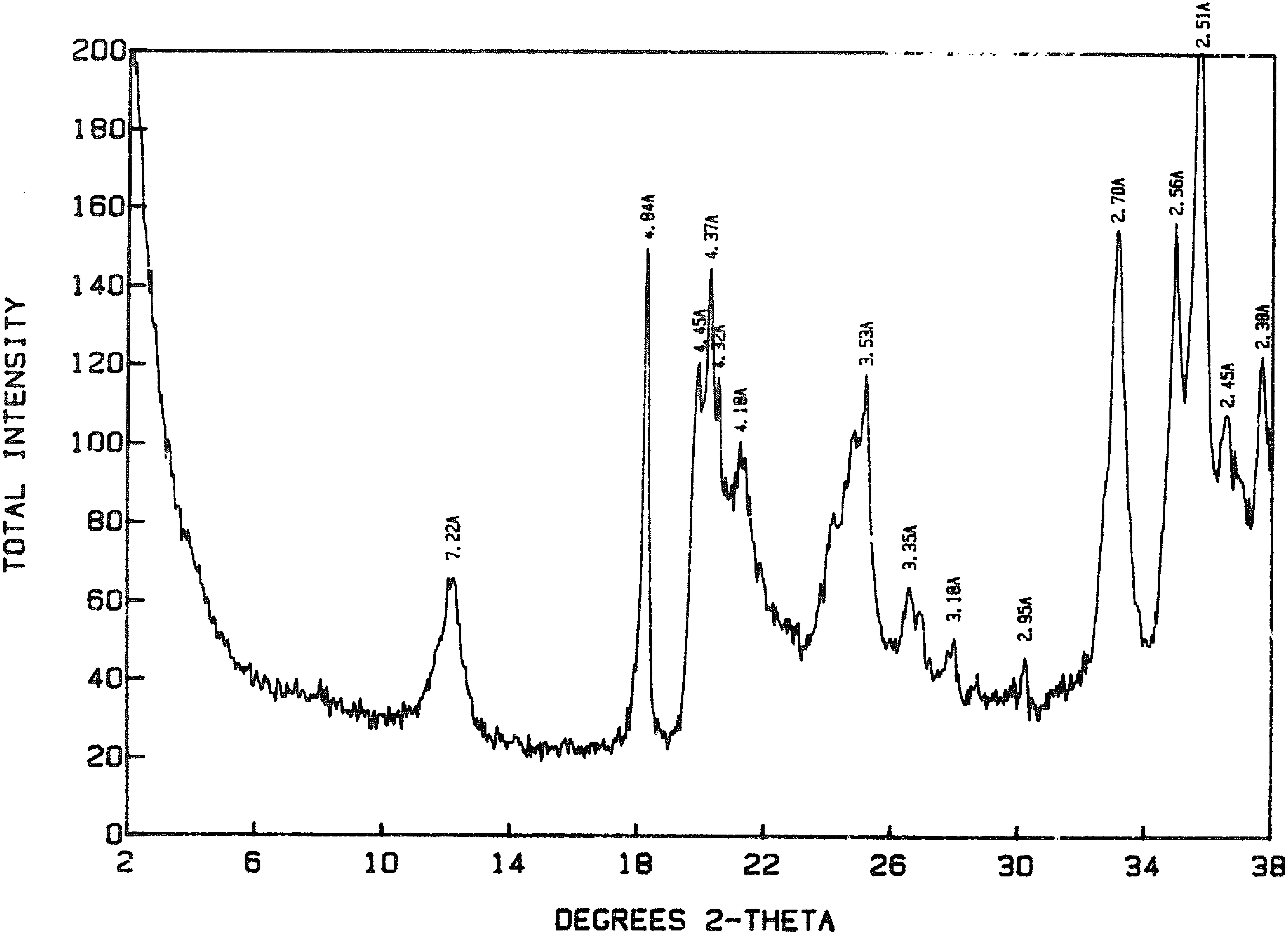

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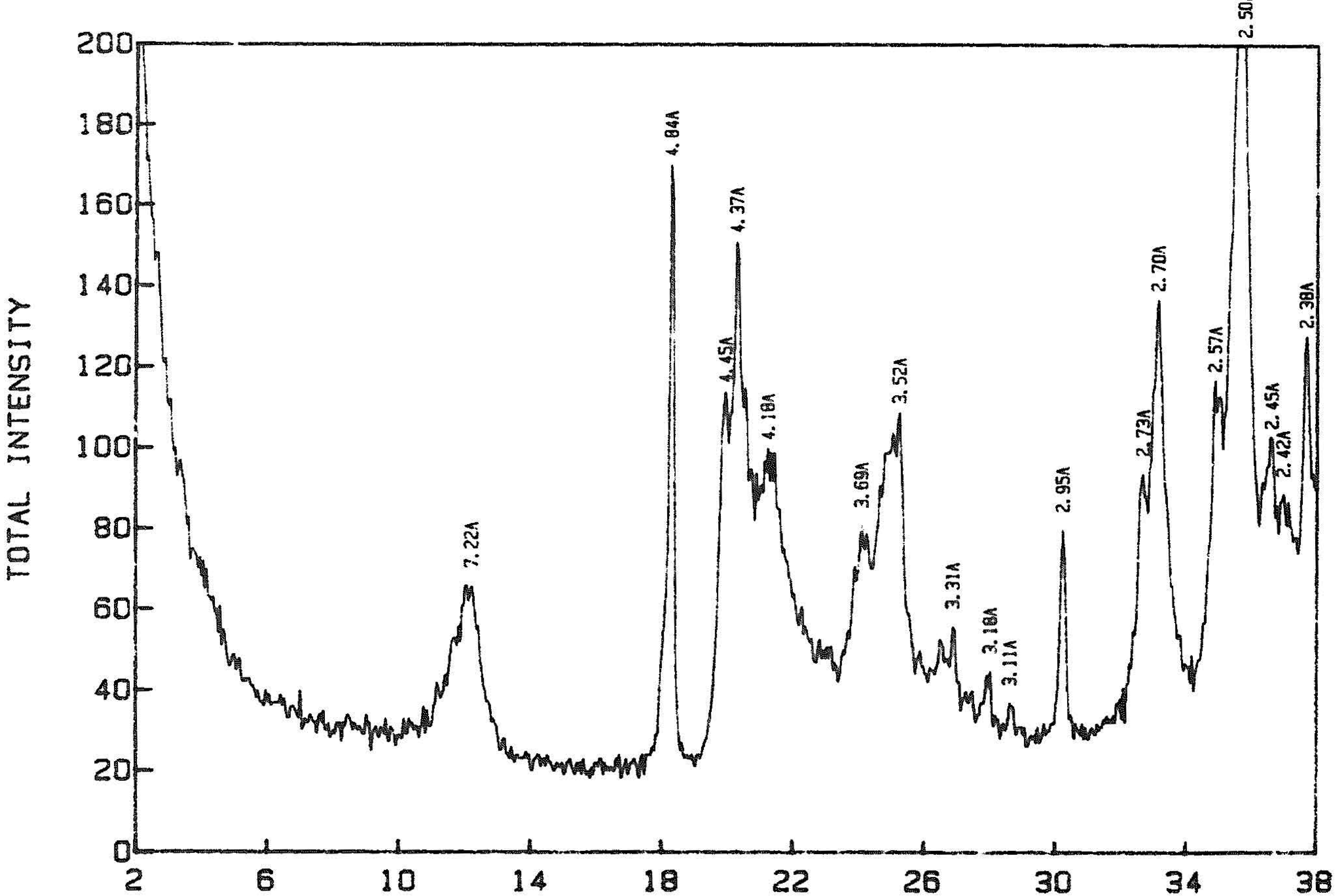

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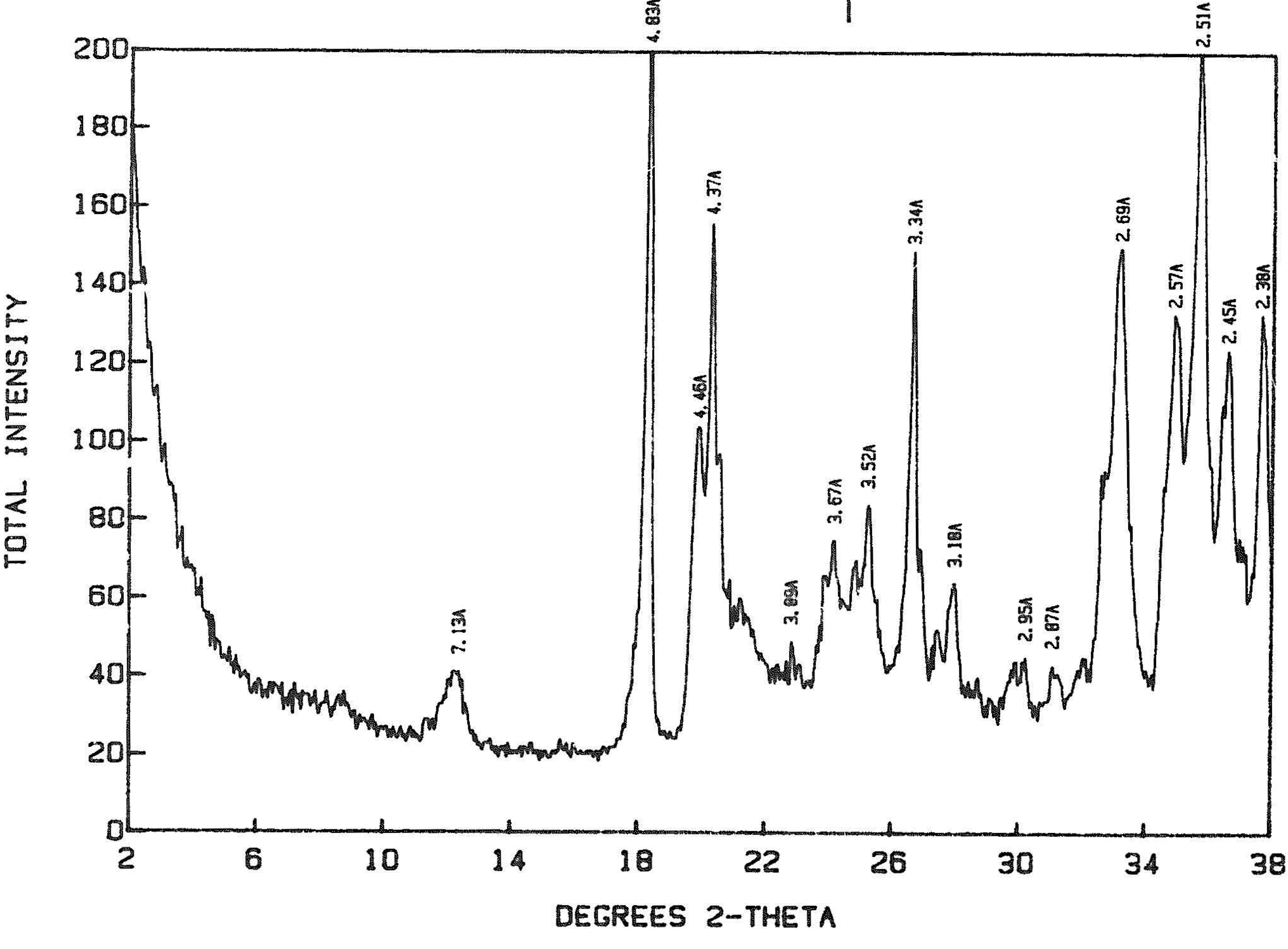

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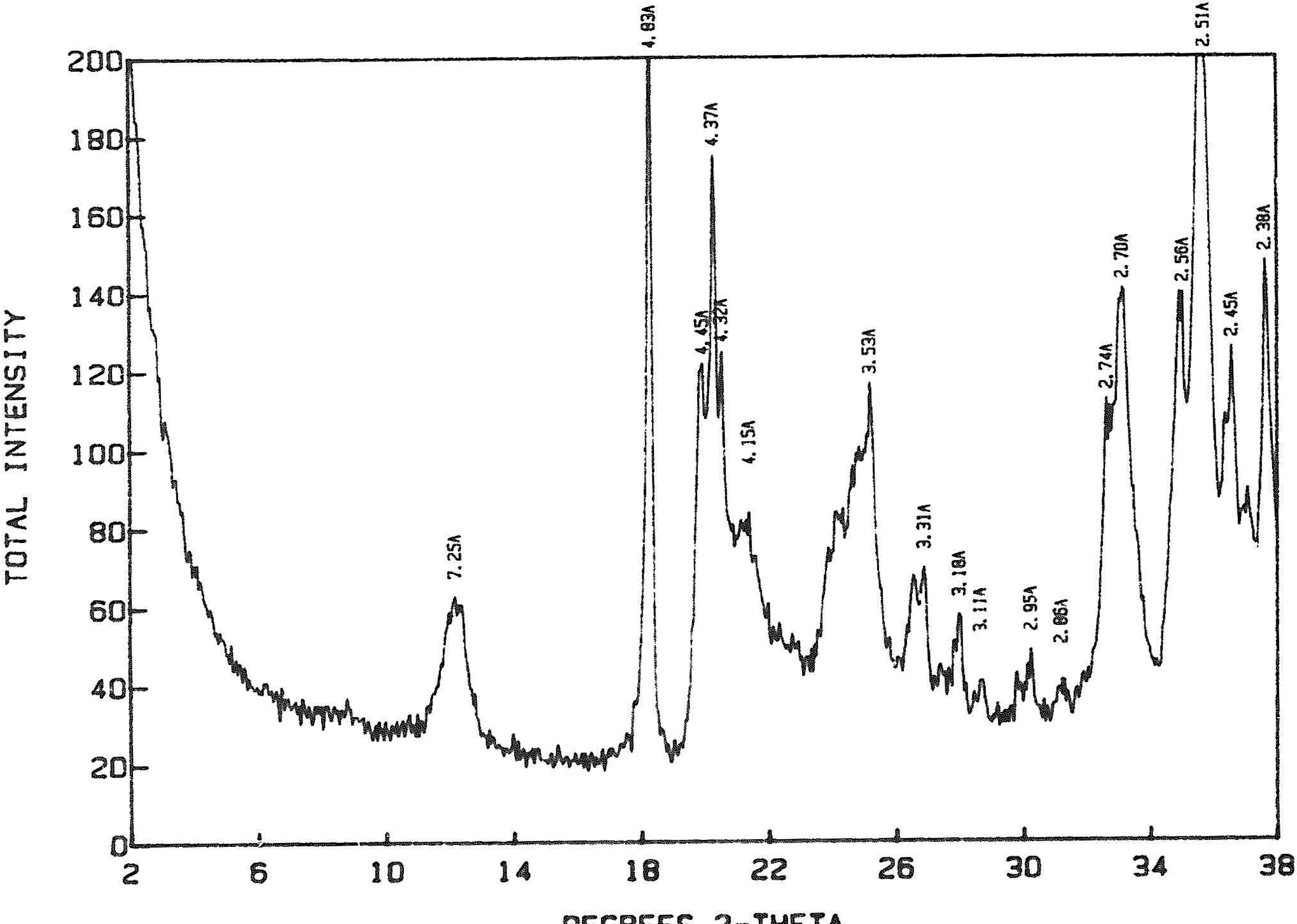

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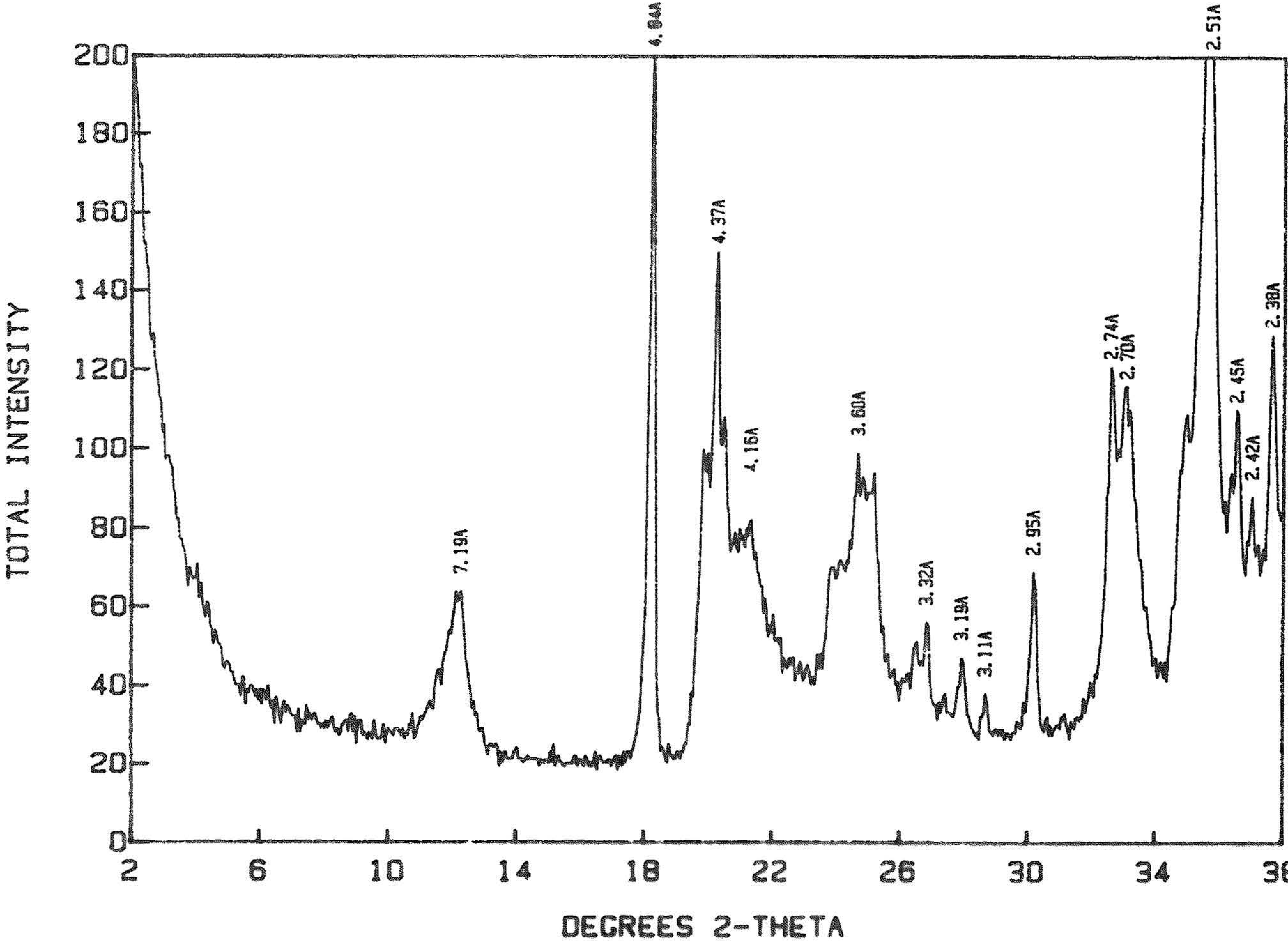

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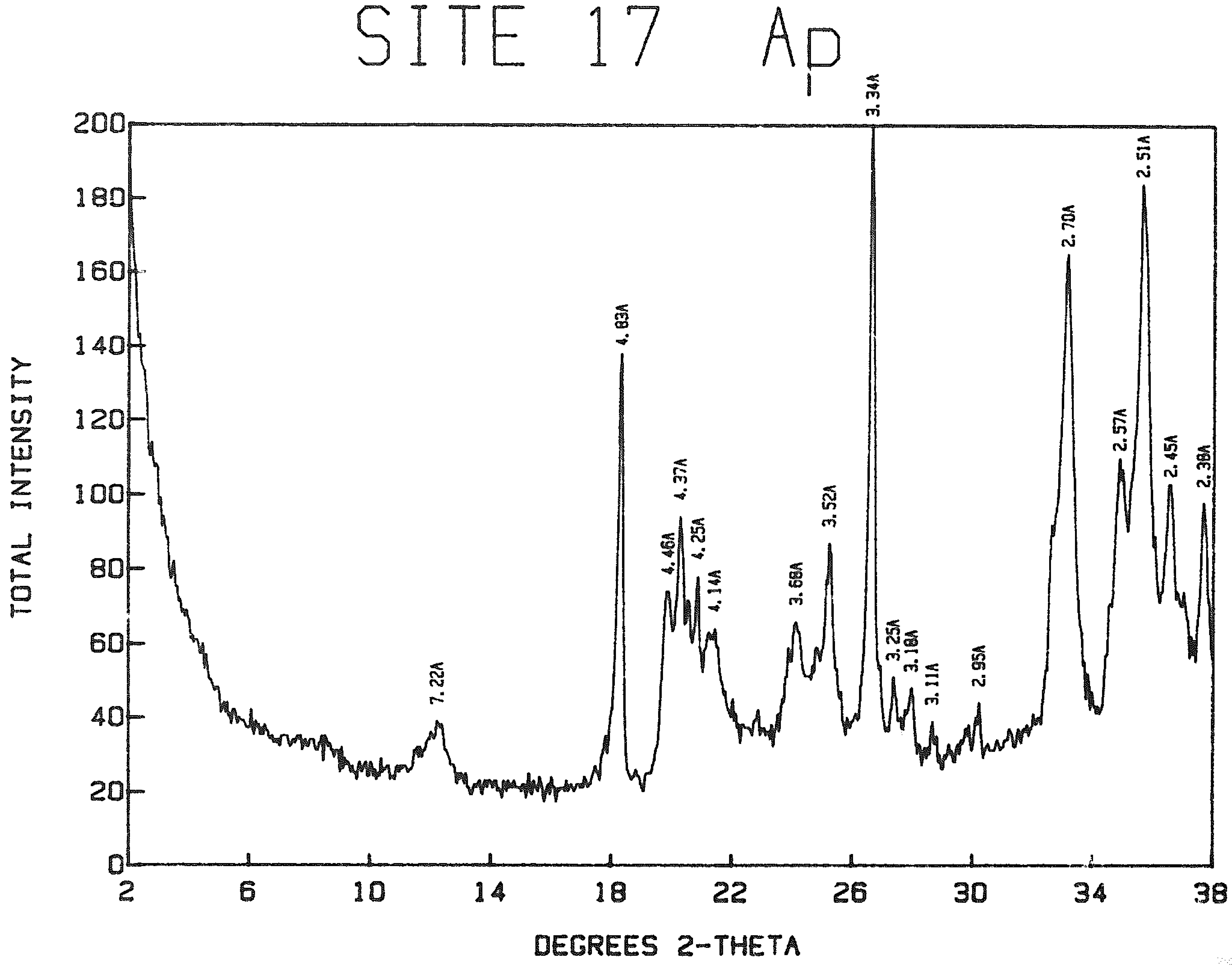

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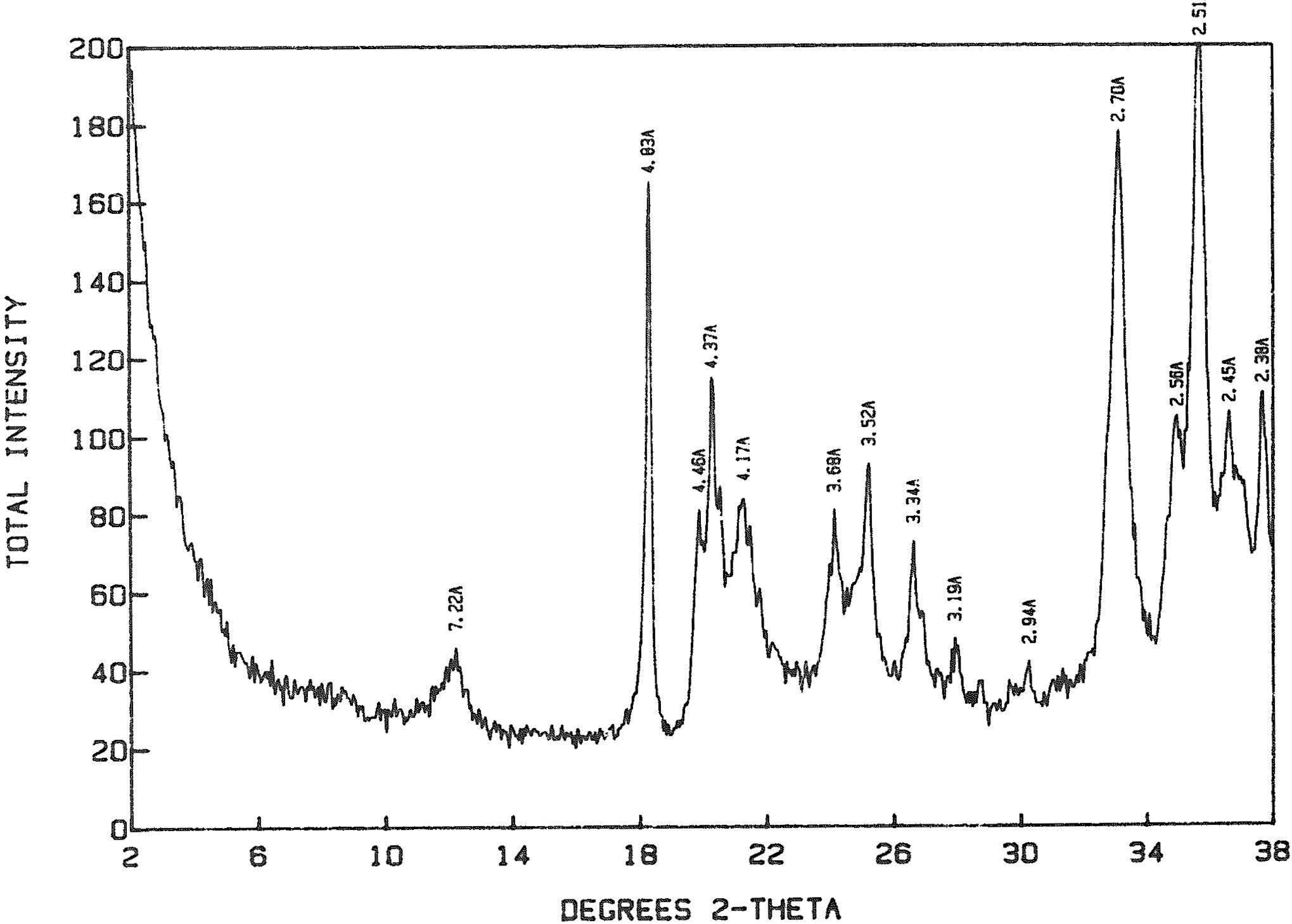

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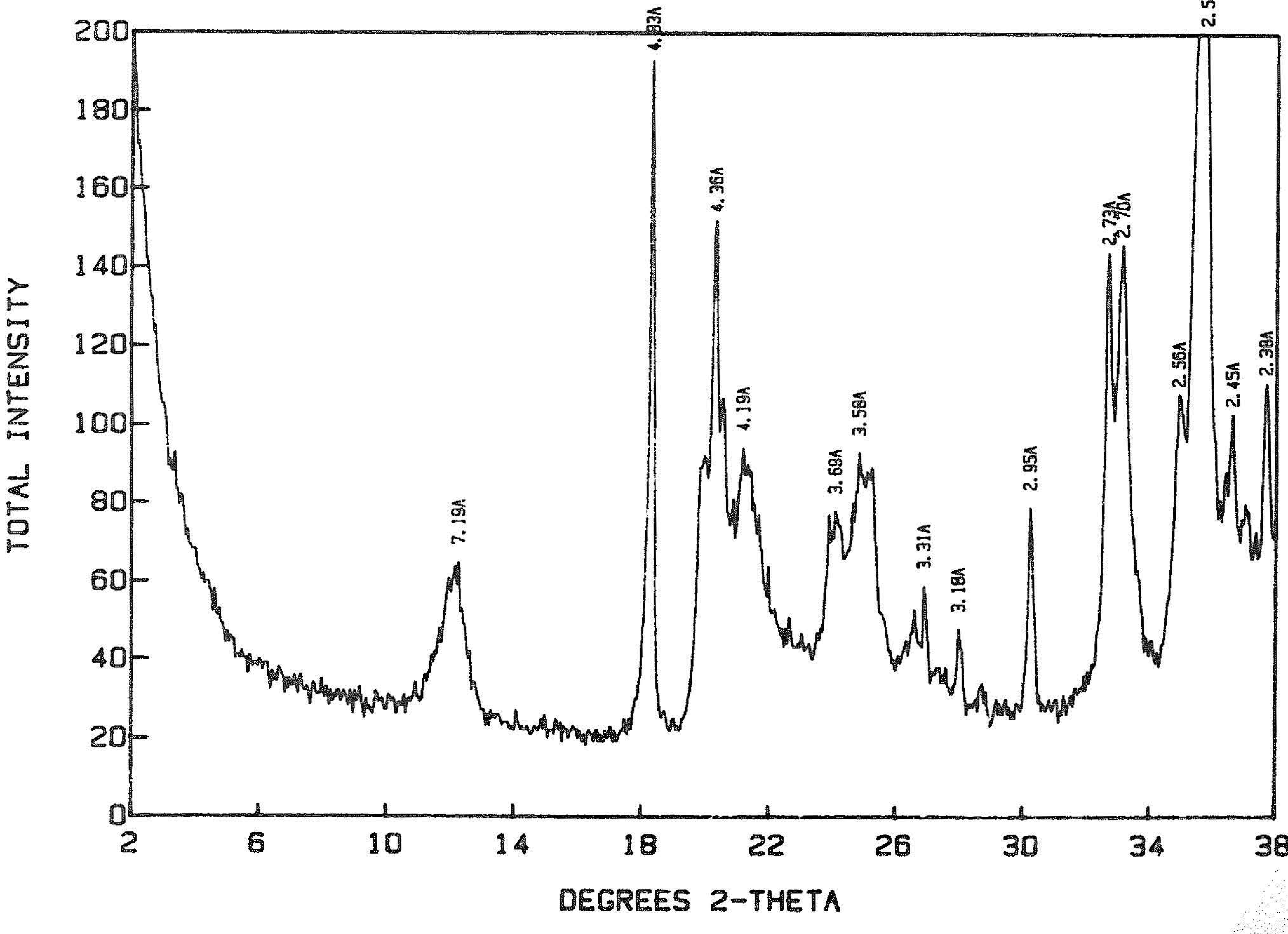

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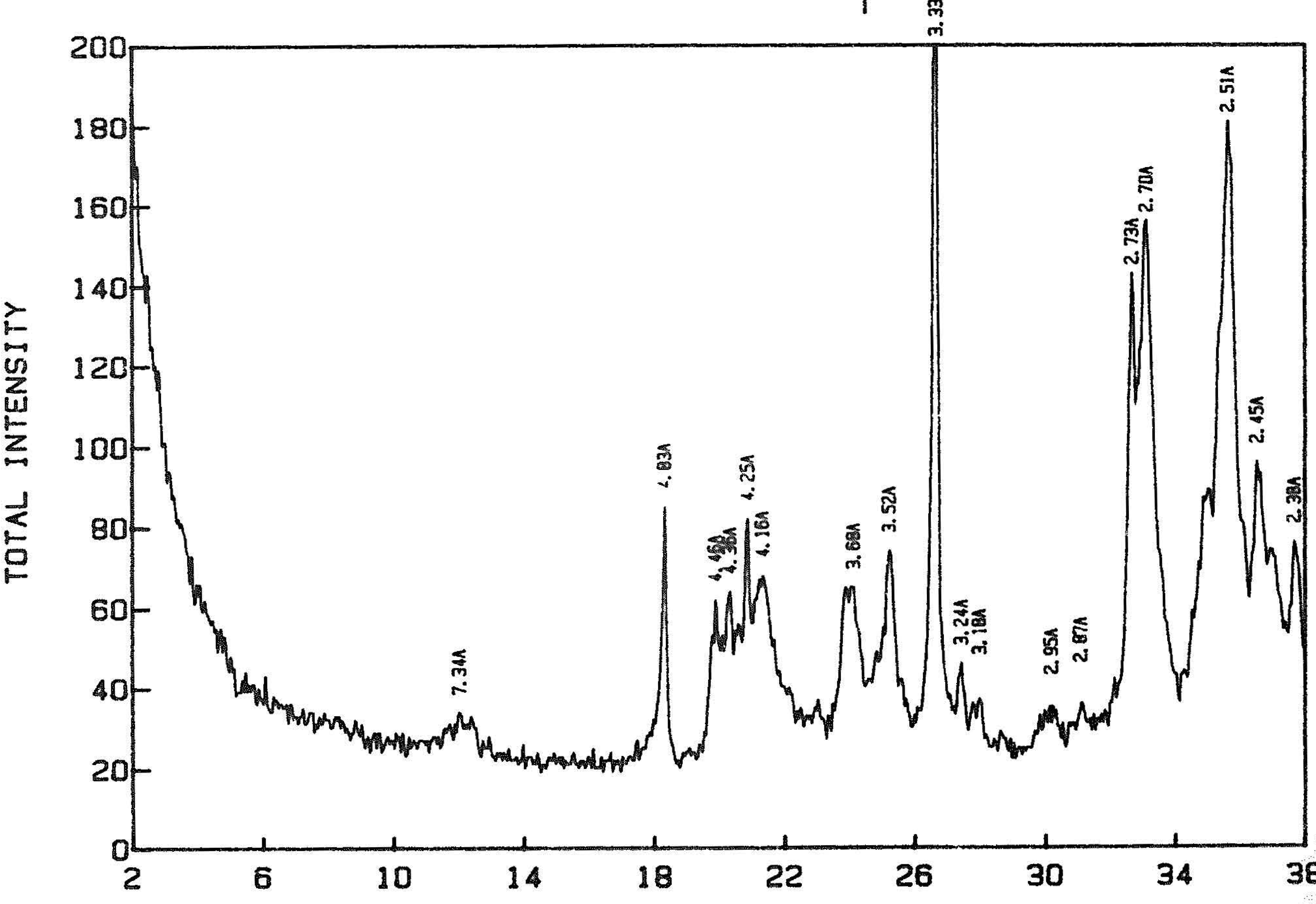

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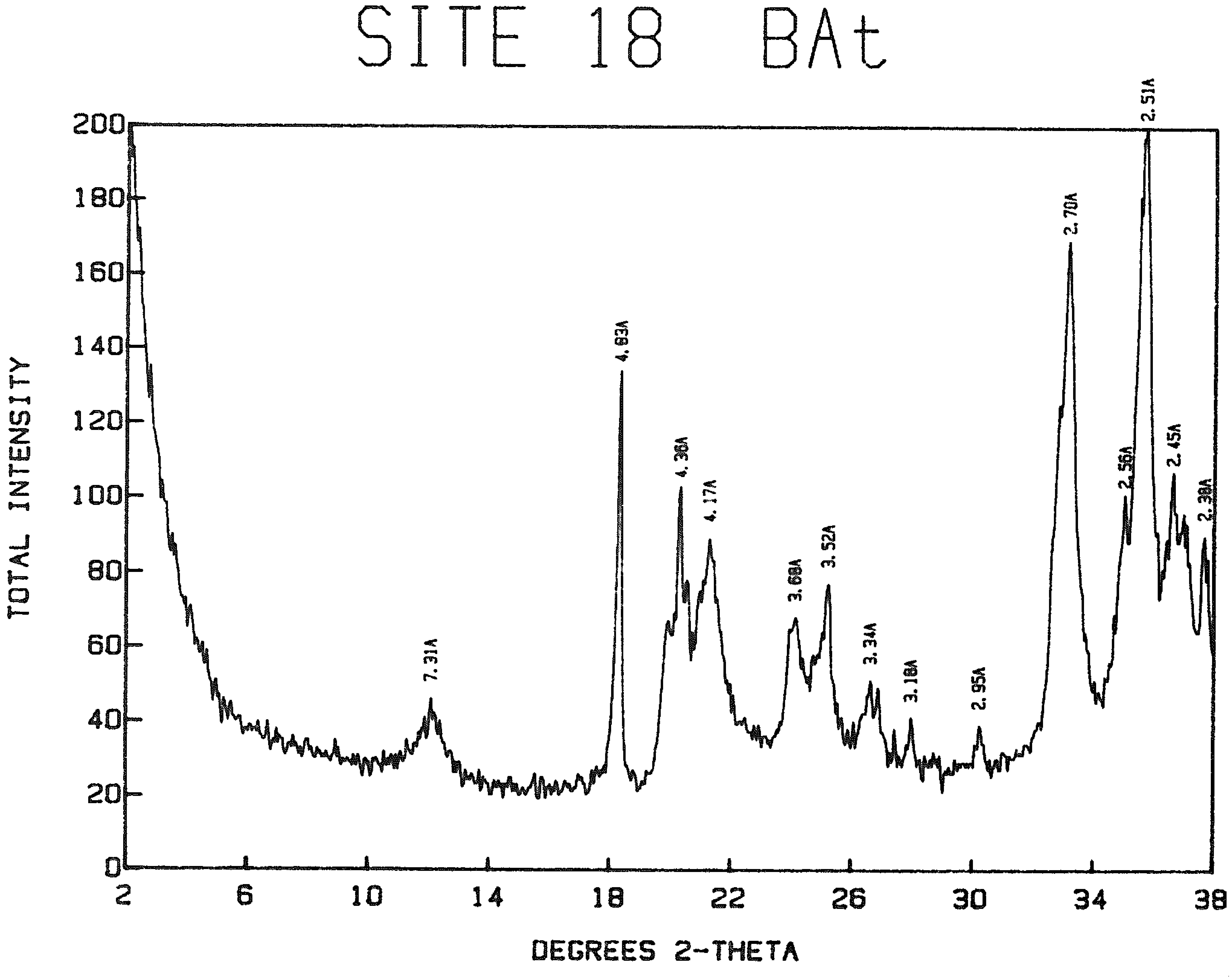

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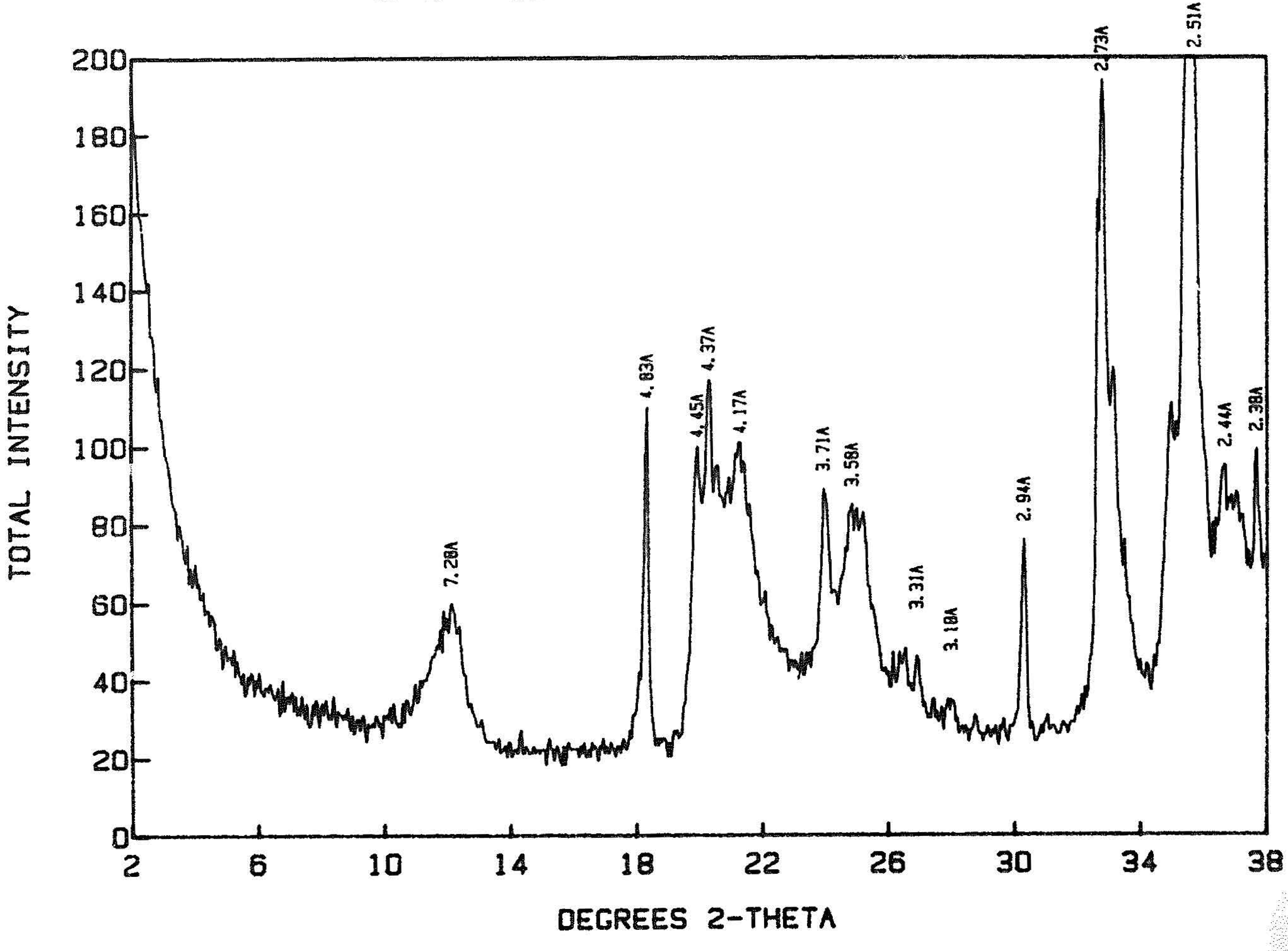

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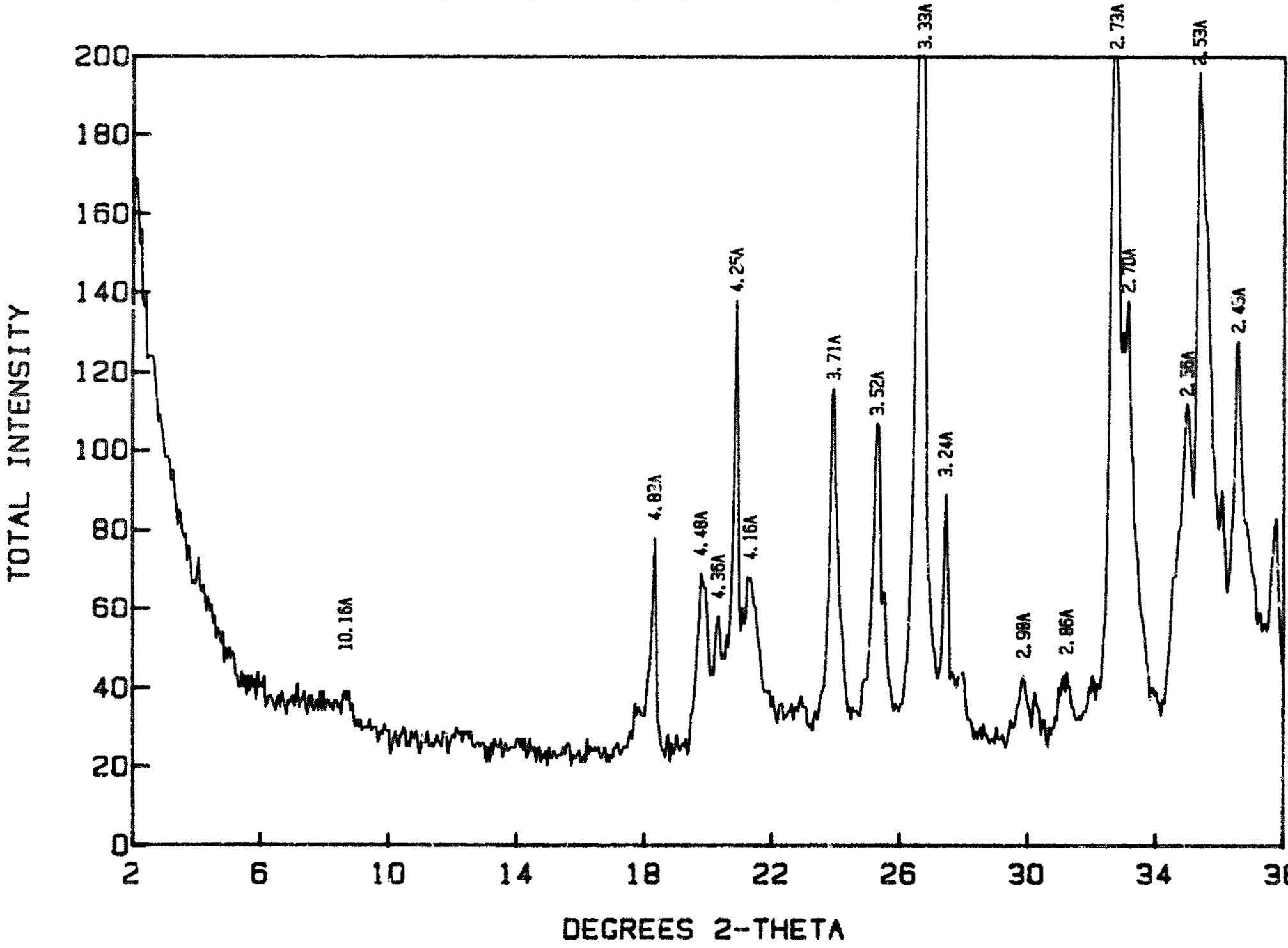

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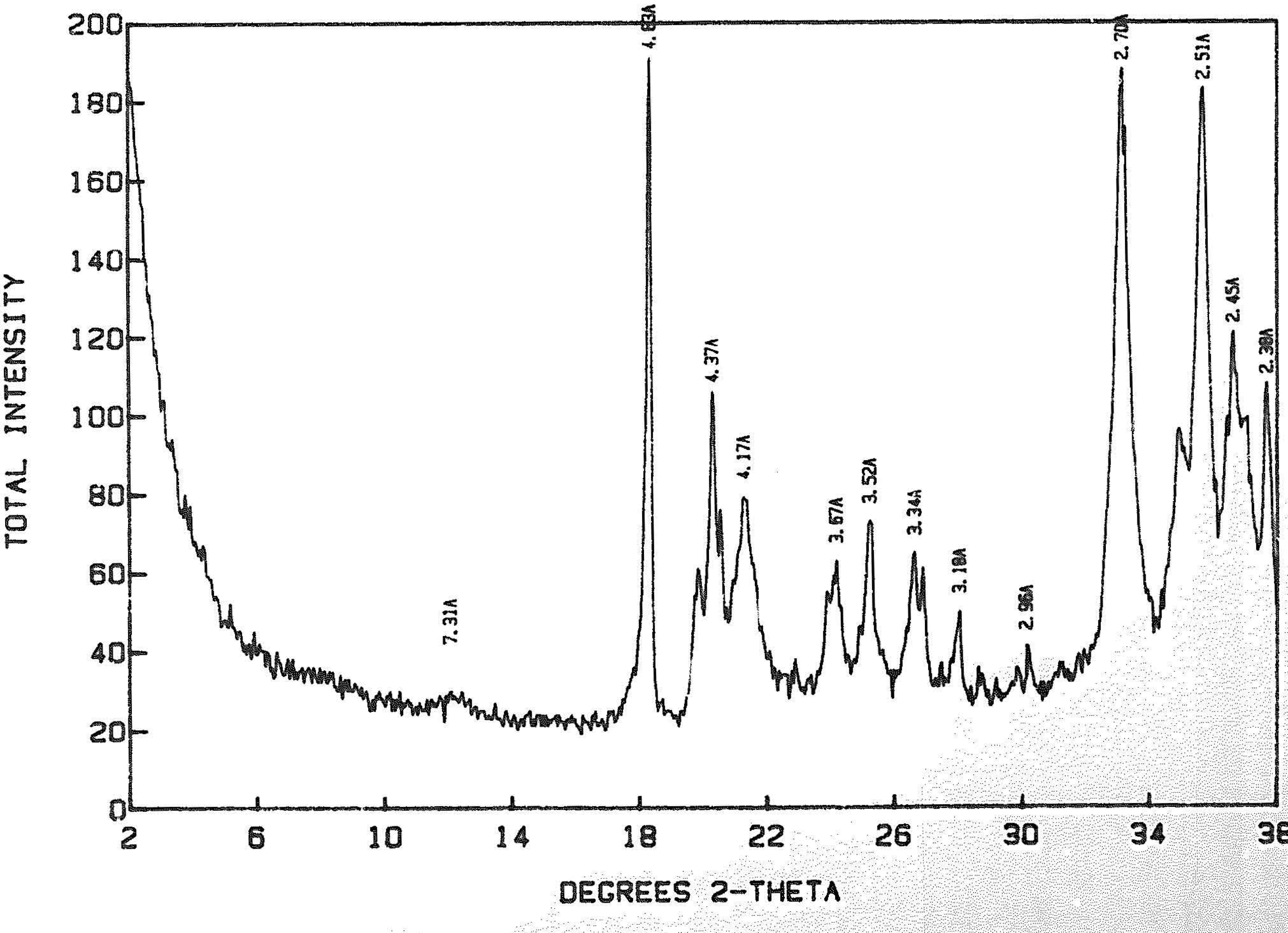

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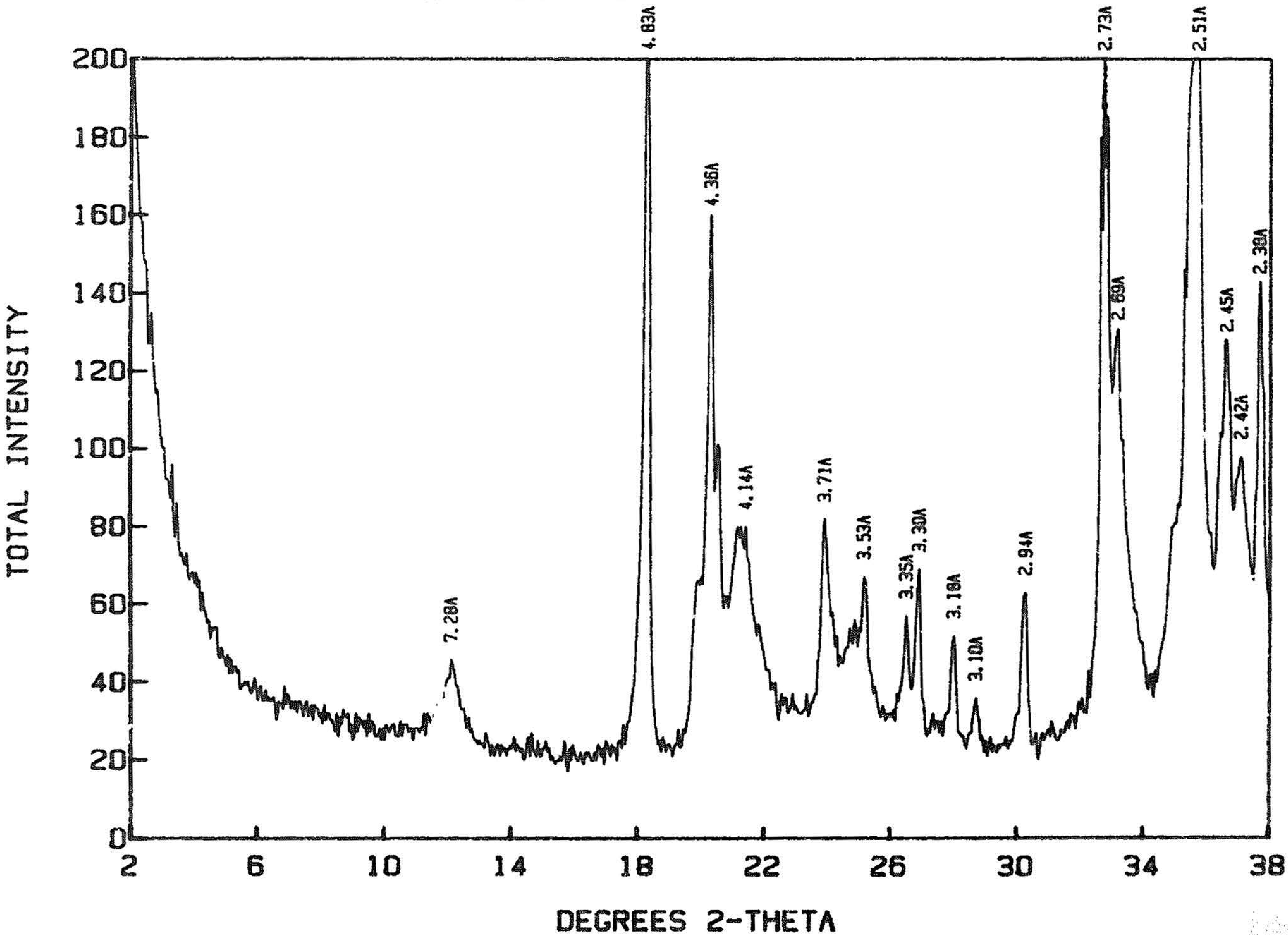

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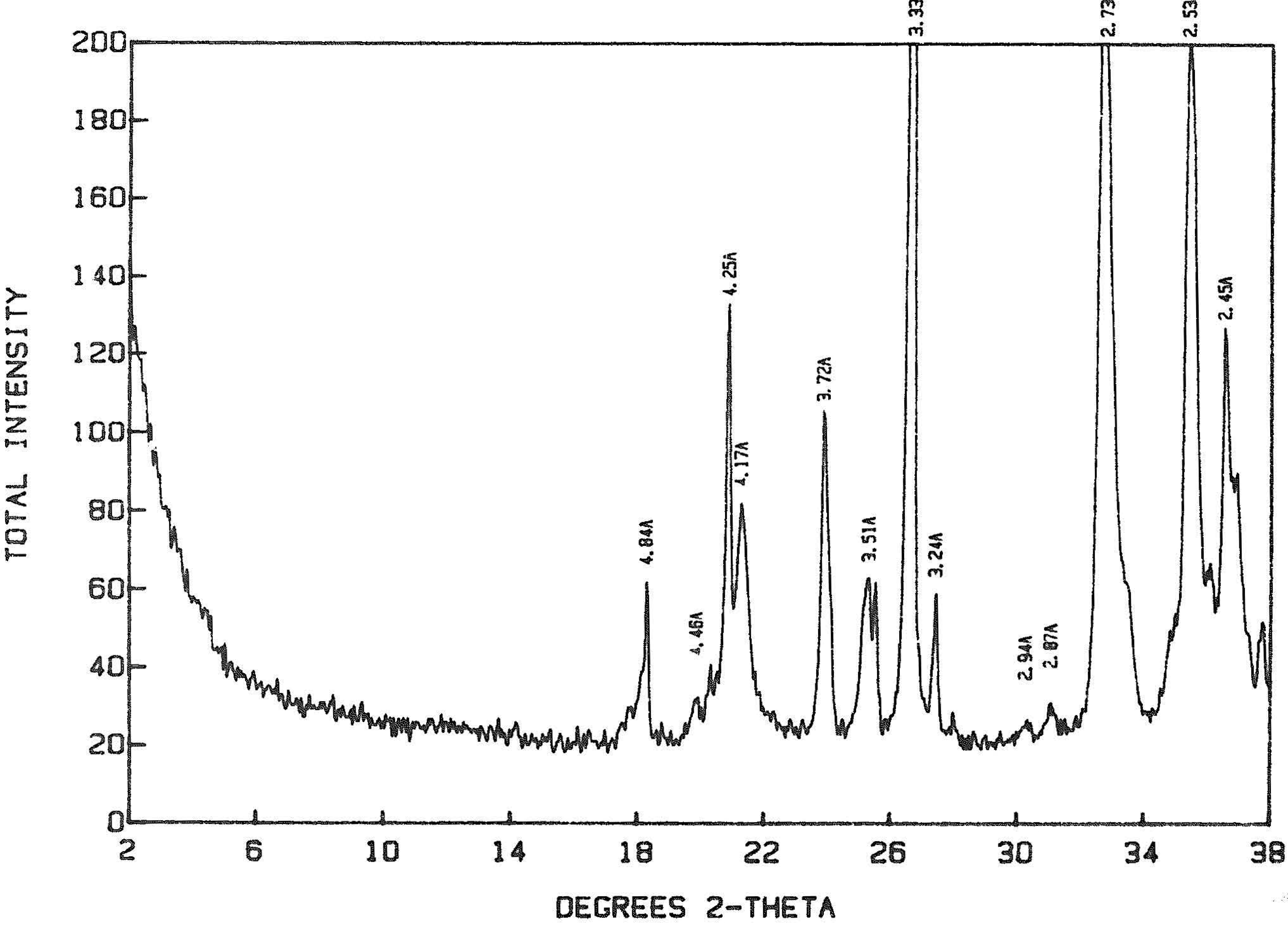

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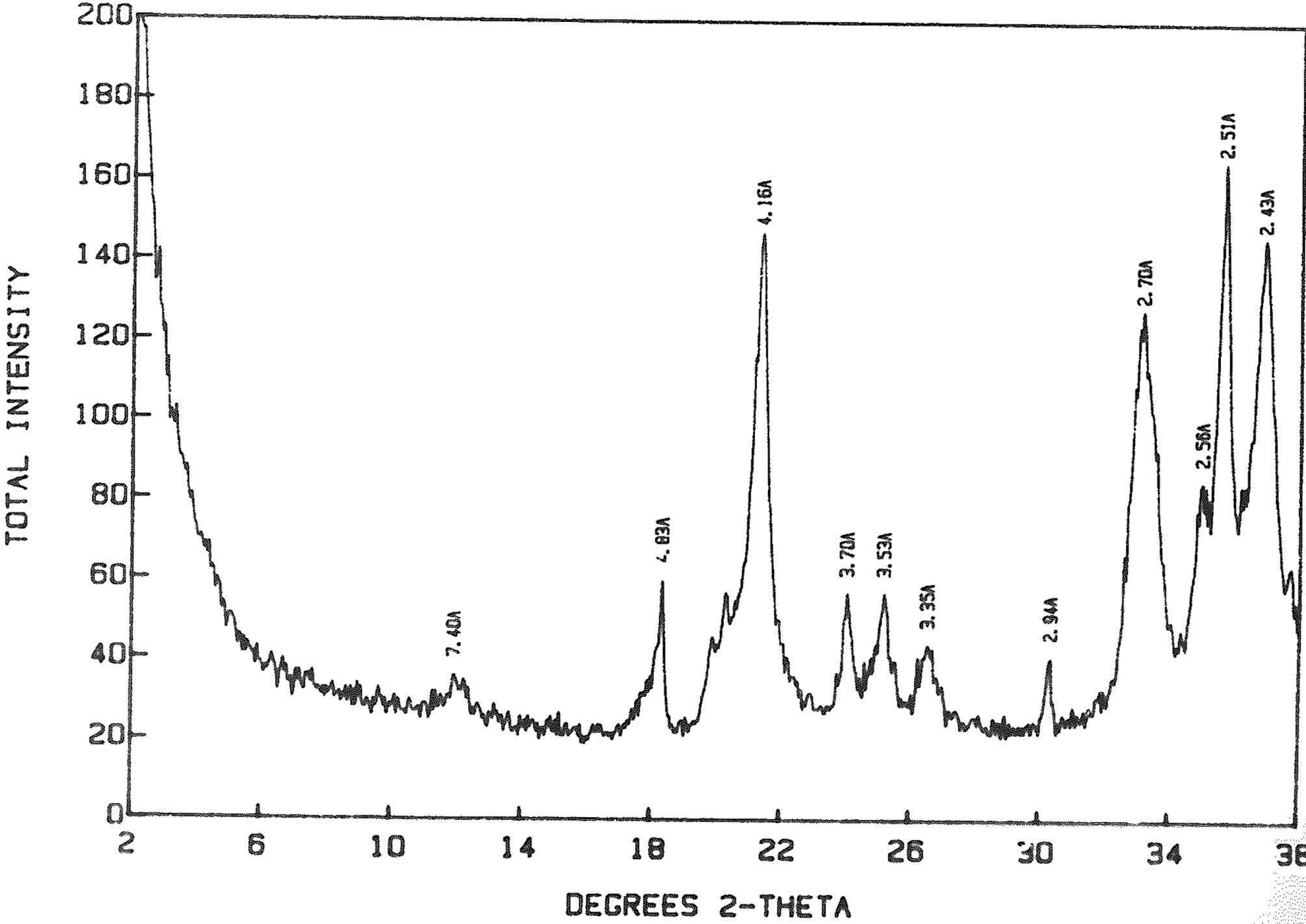

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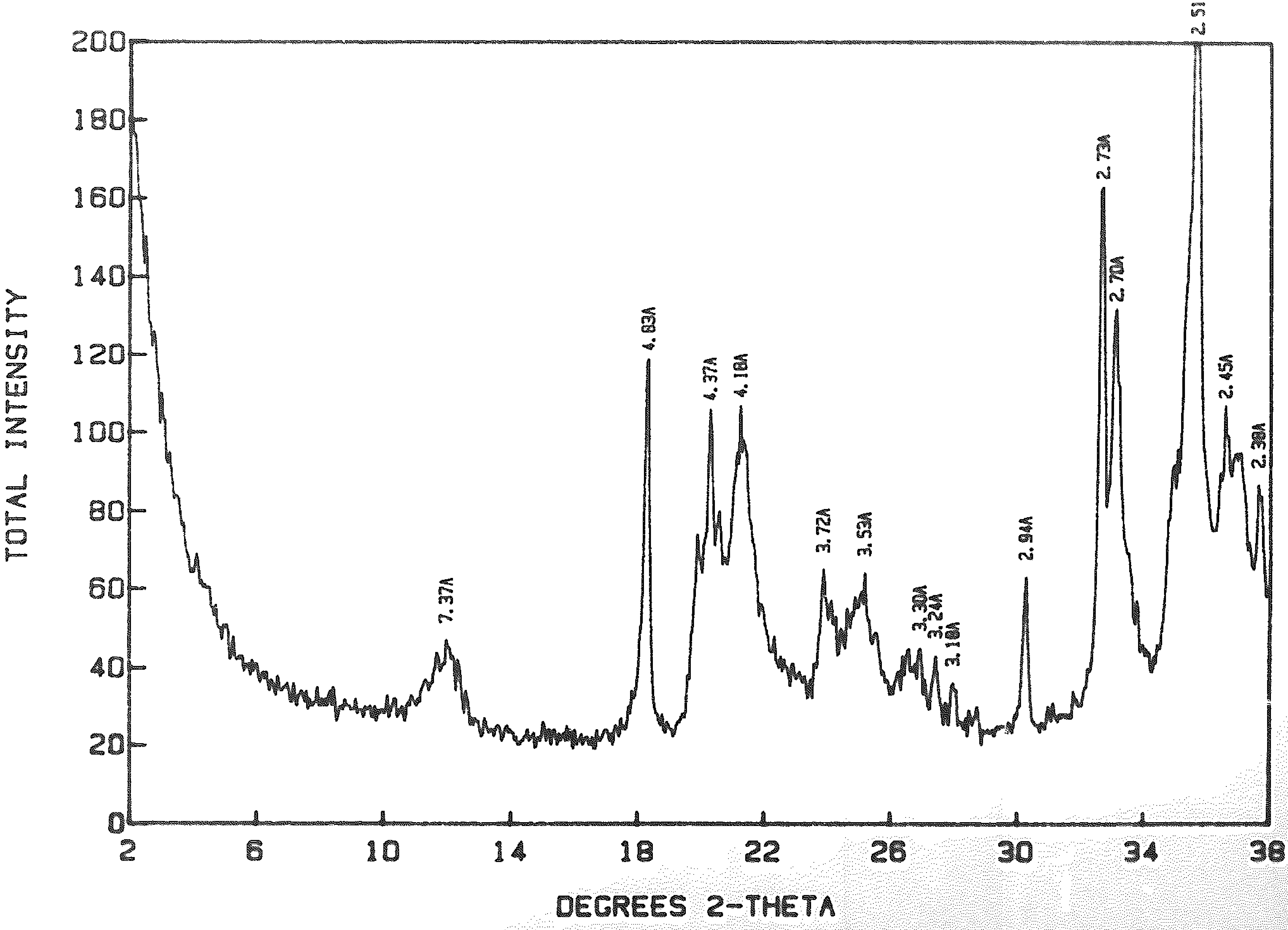

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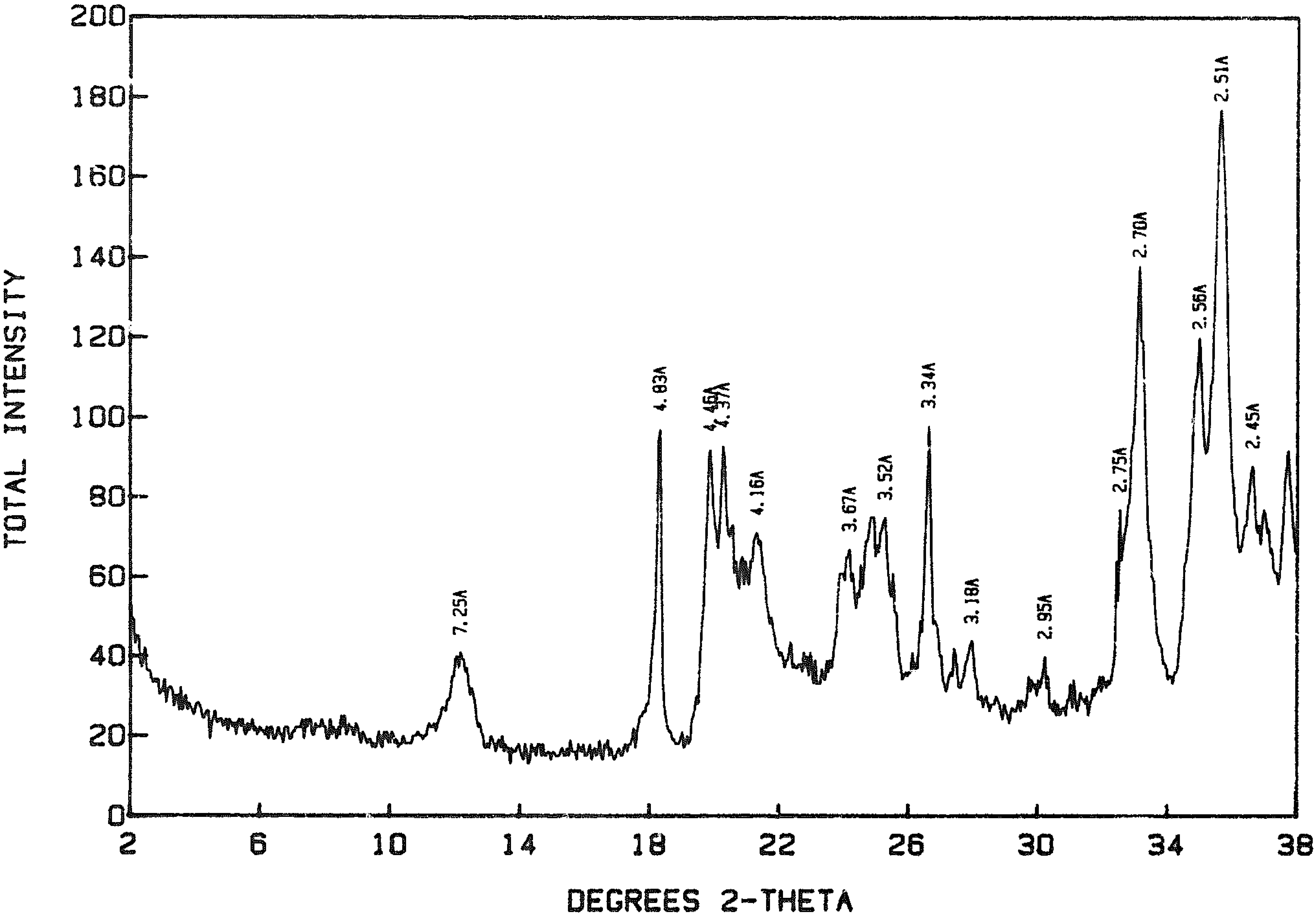

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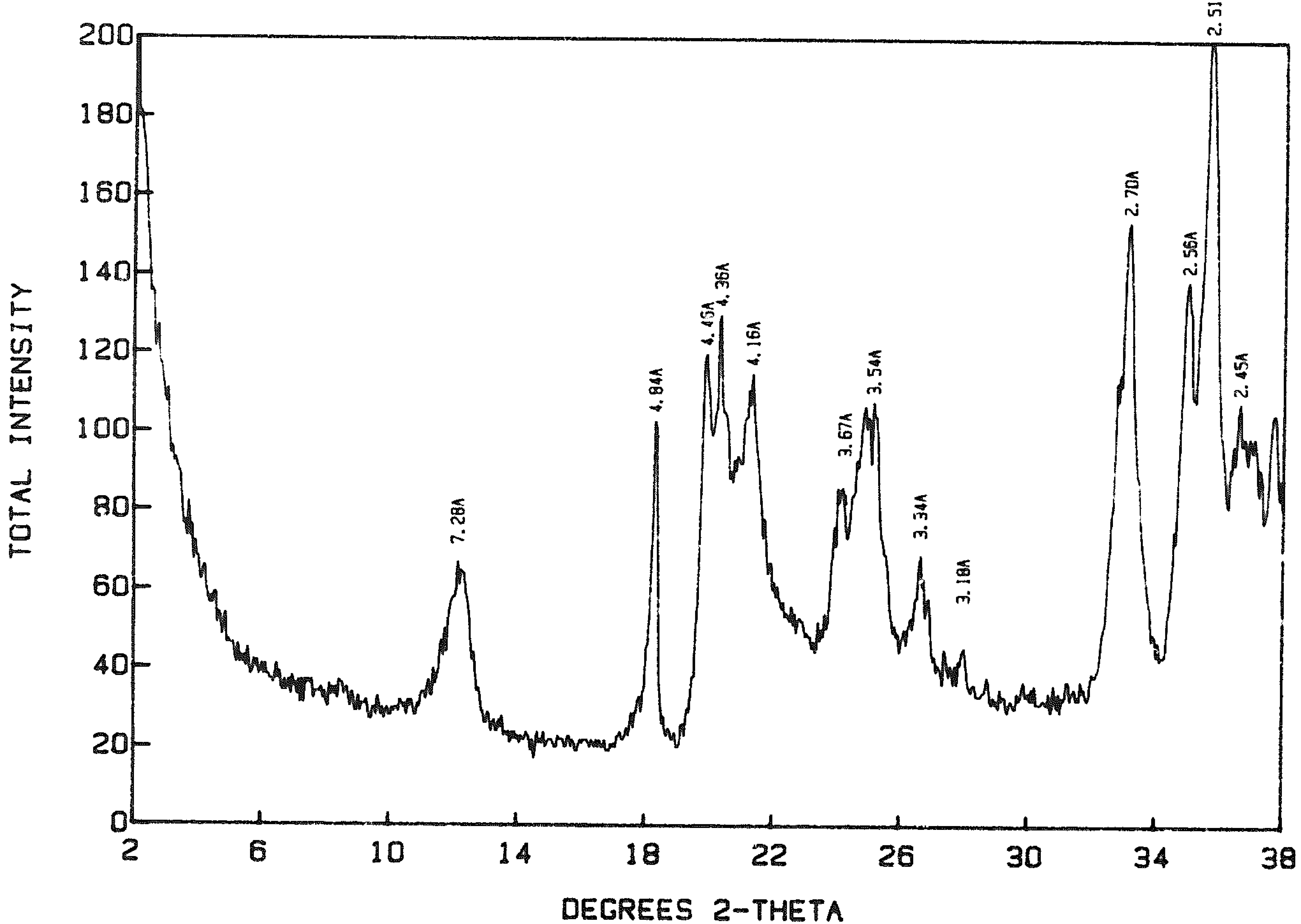

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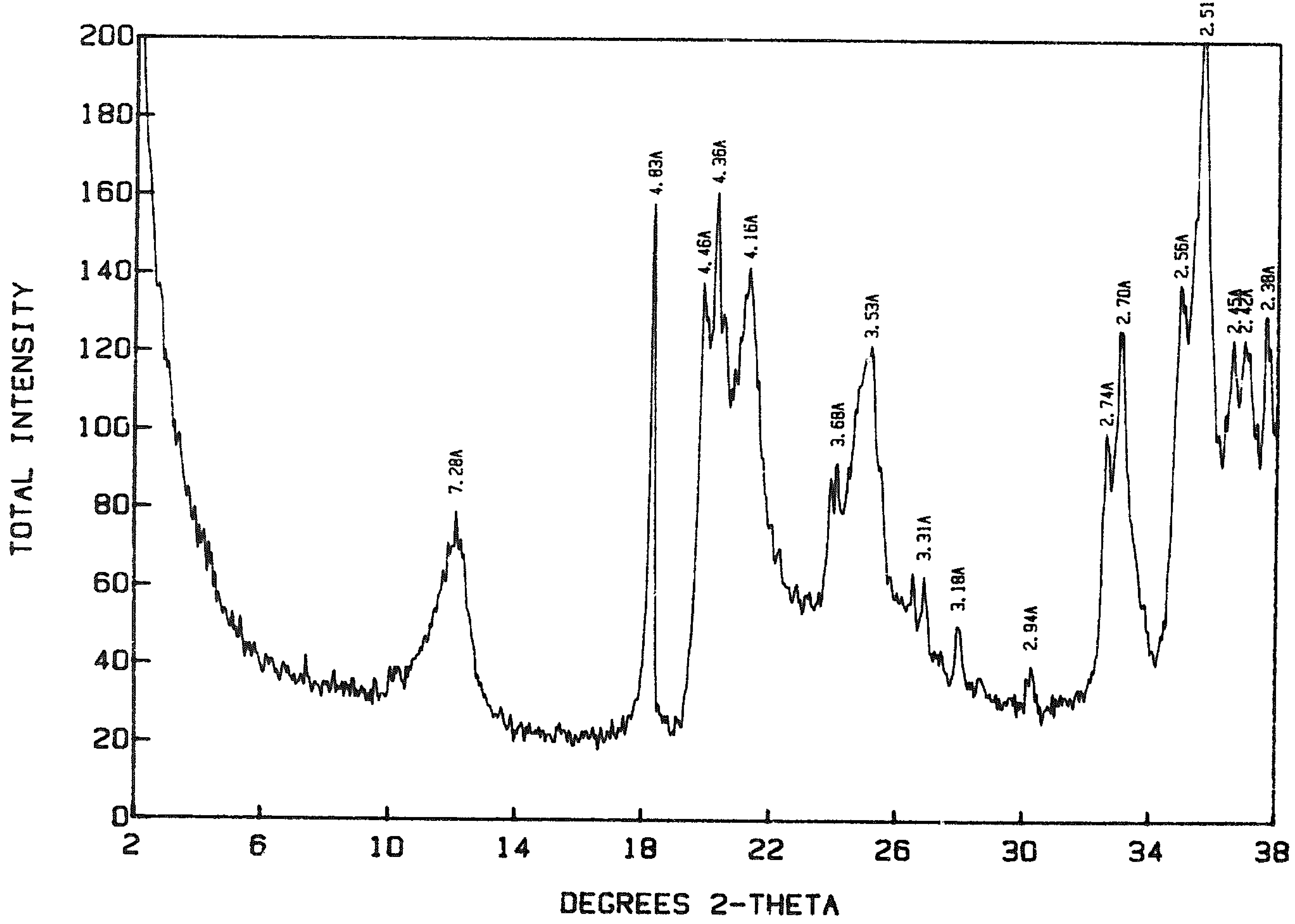

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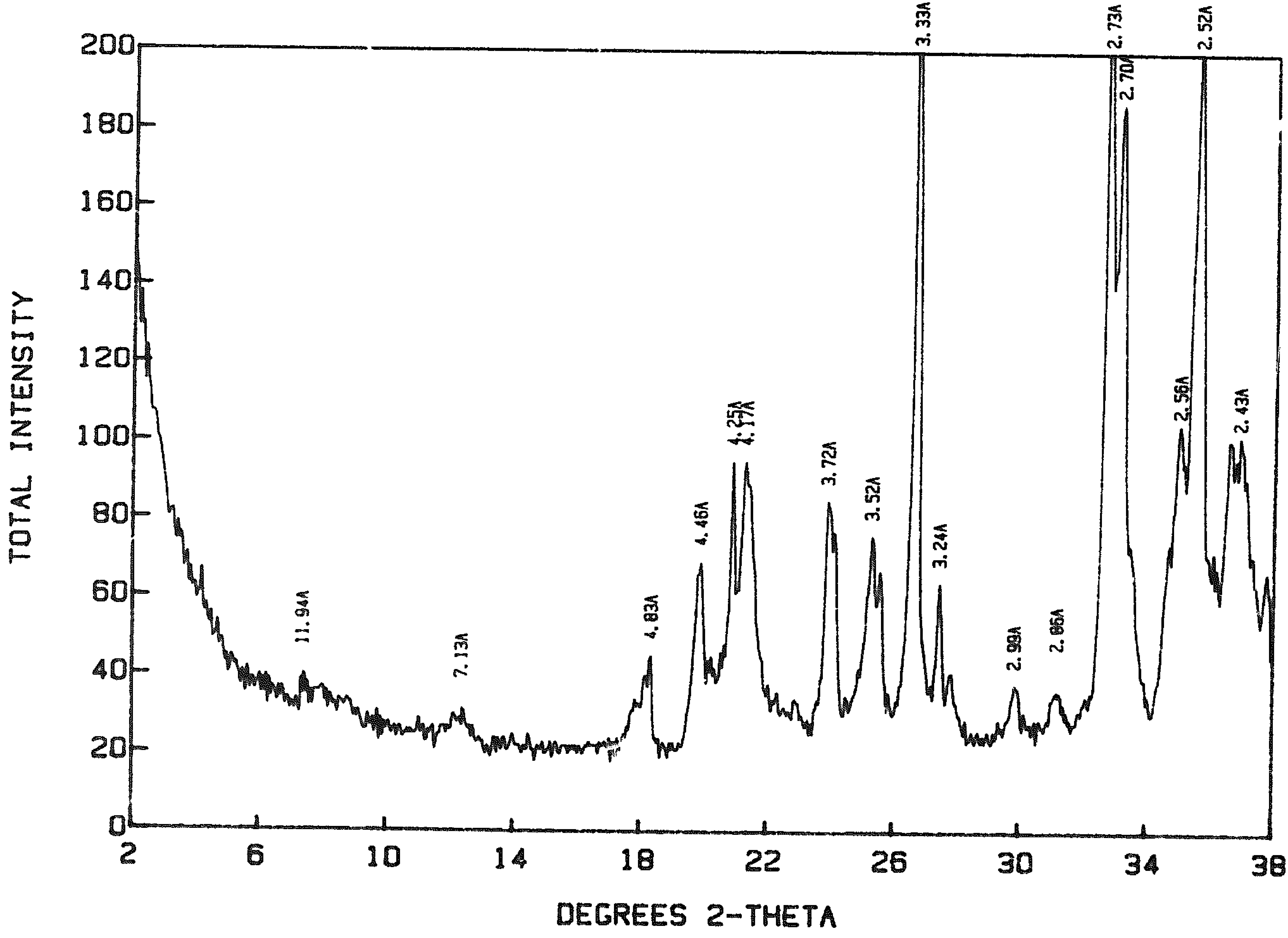

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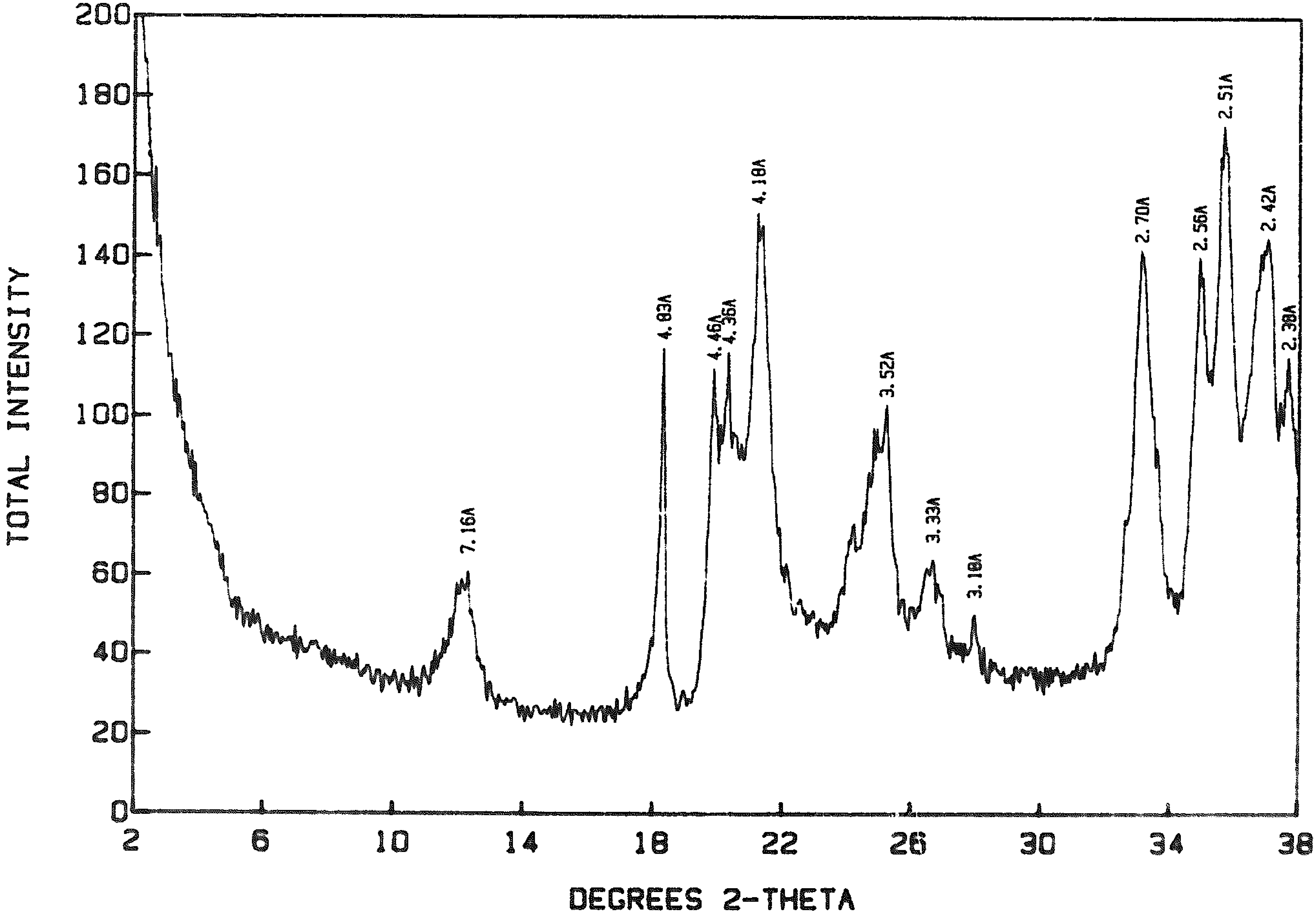

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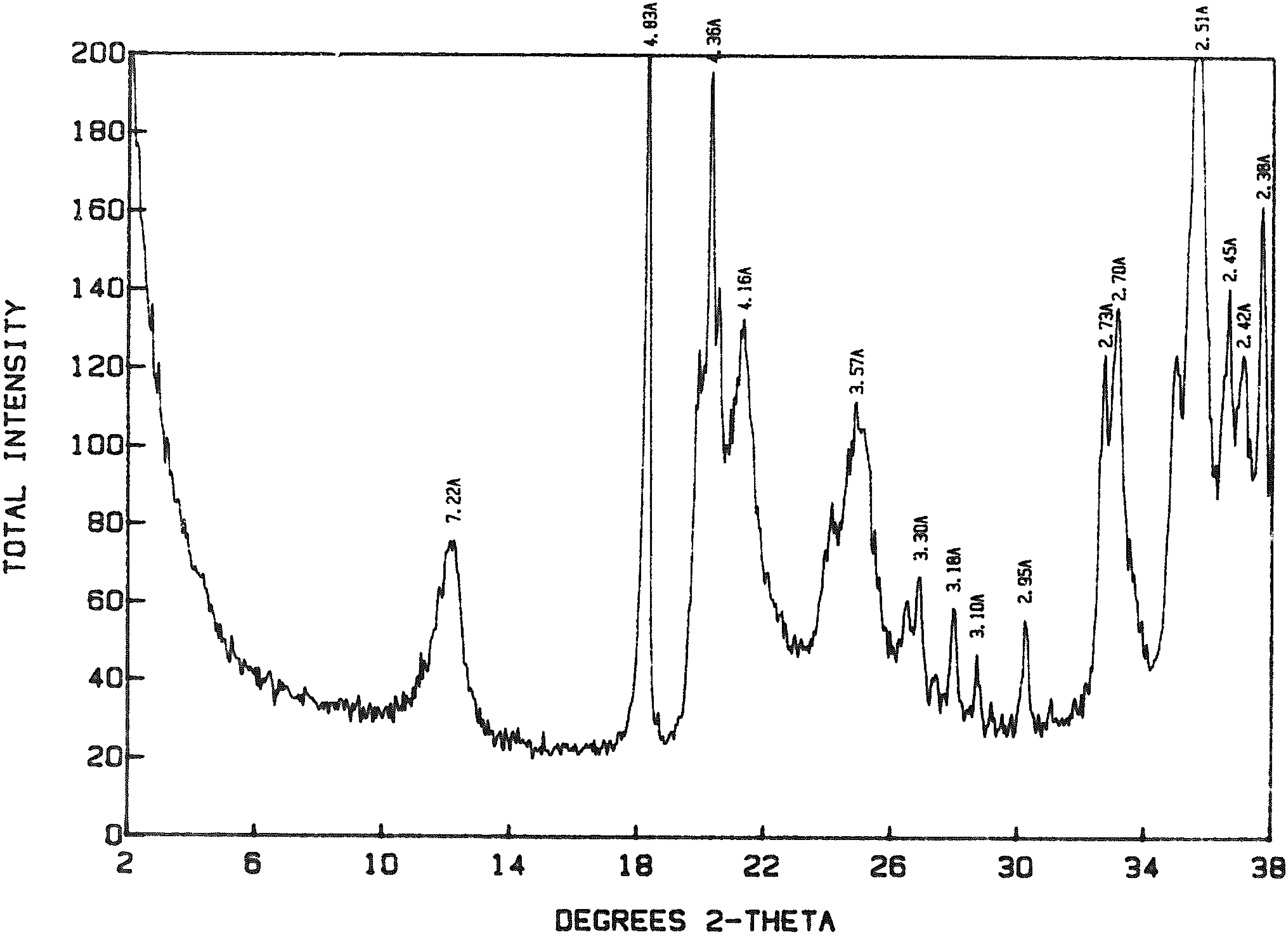

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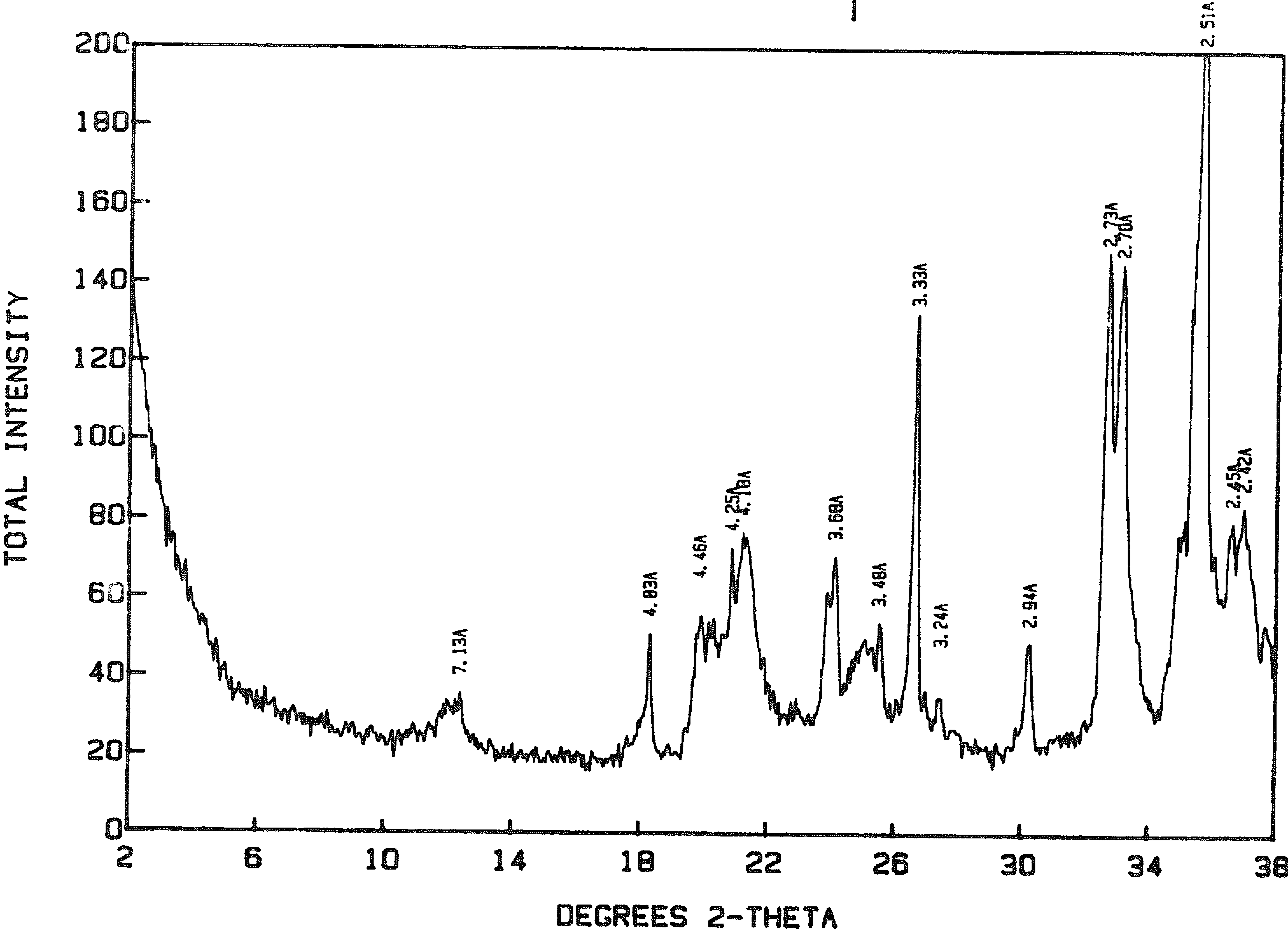
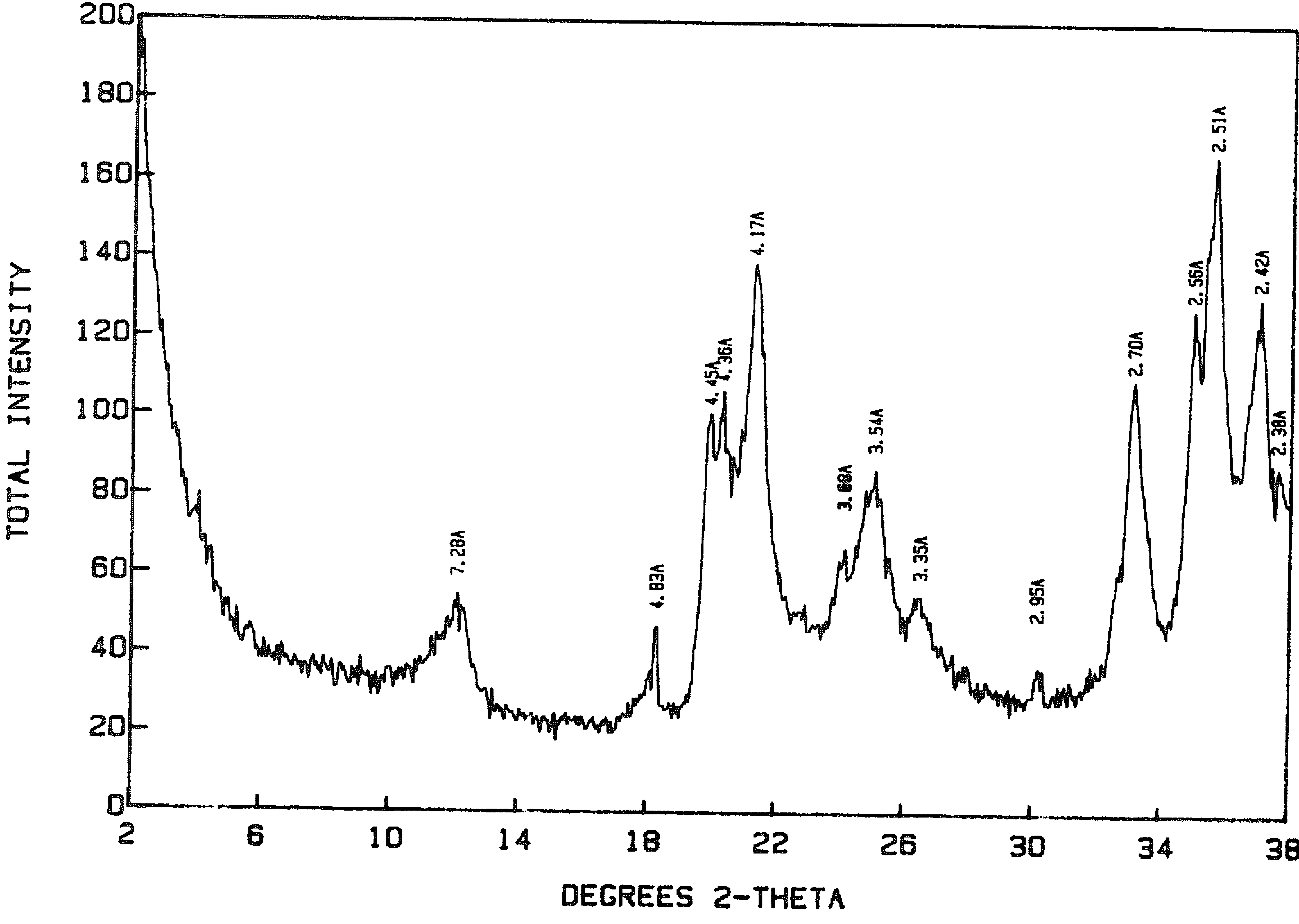


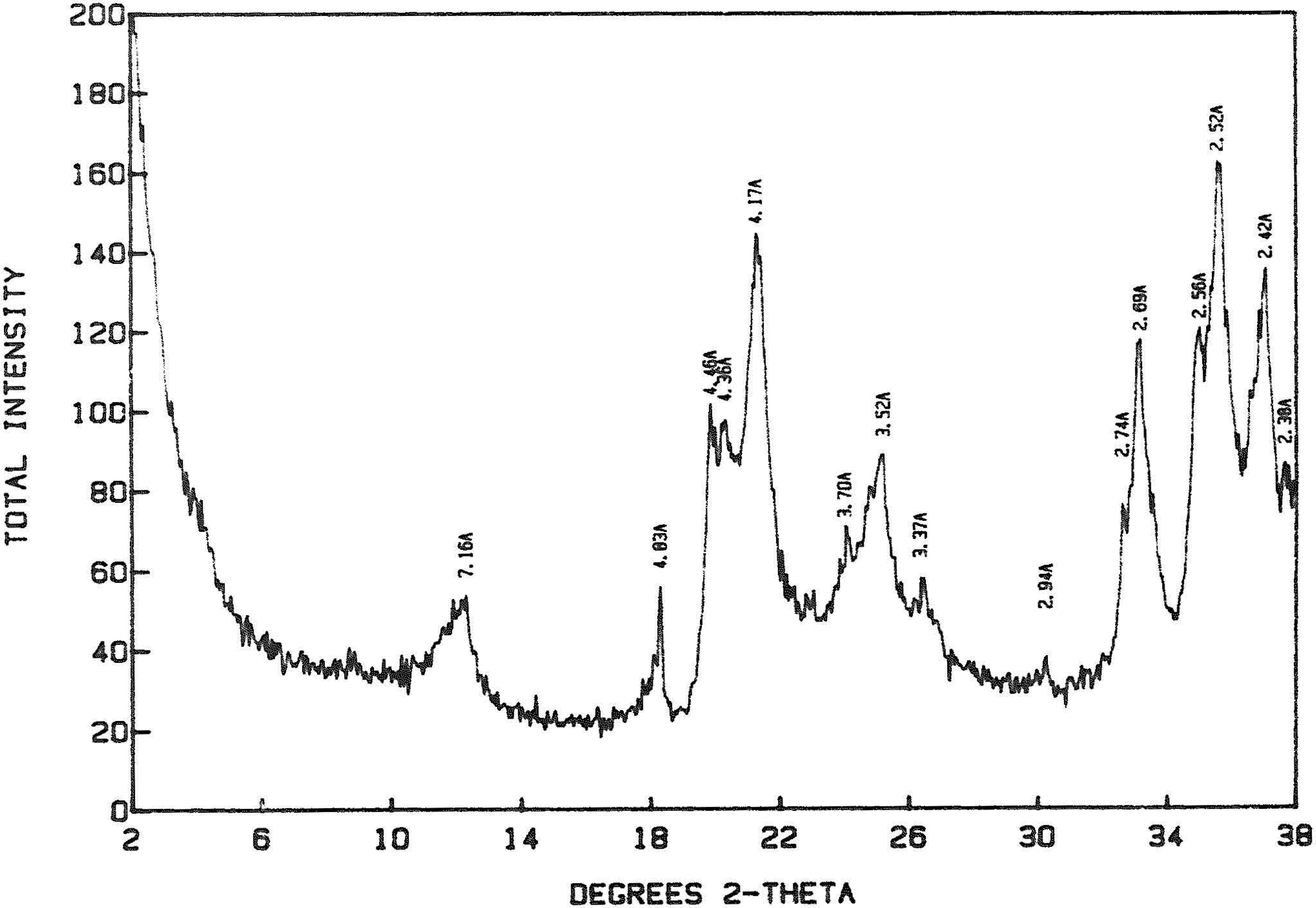
Volume Number 117; File Number D880704.4

SITE 14 Bw3



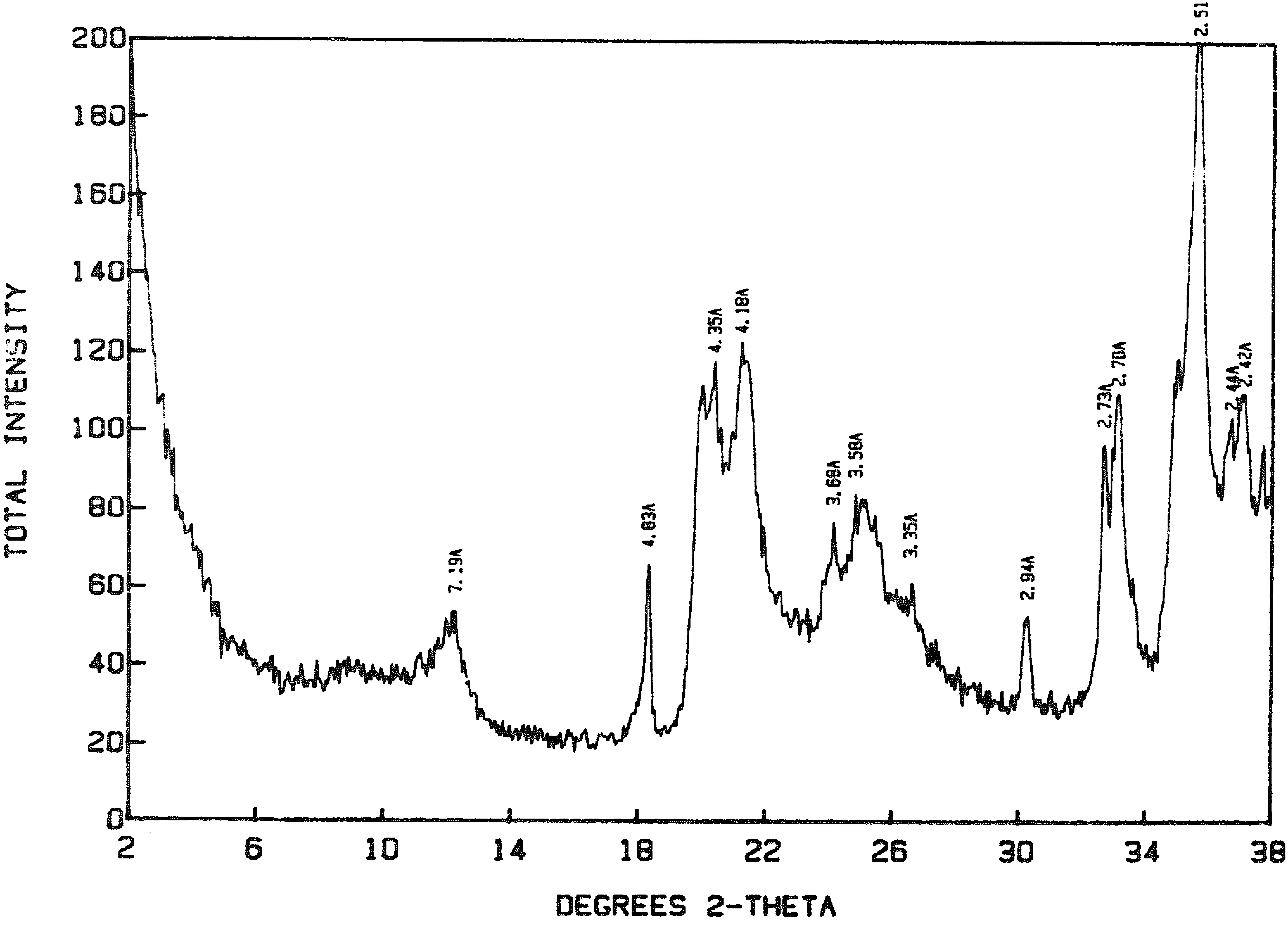
Volume Number 92; File Number D880415.3

SITE 14 2Bt1



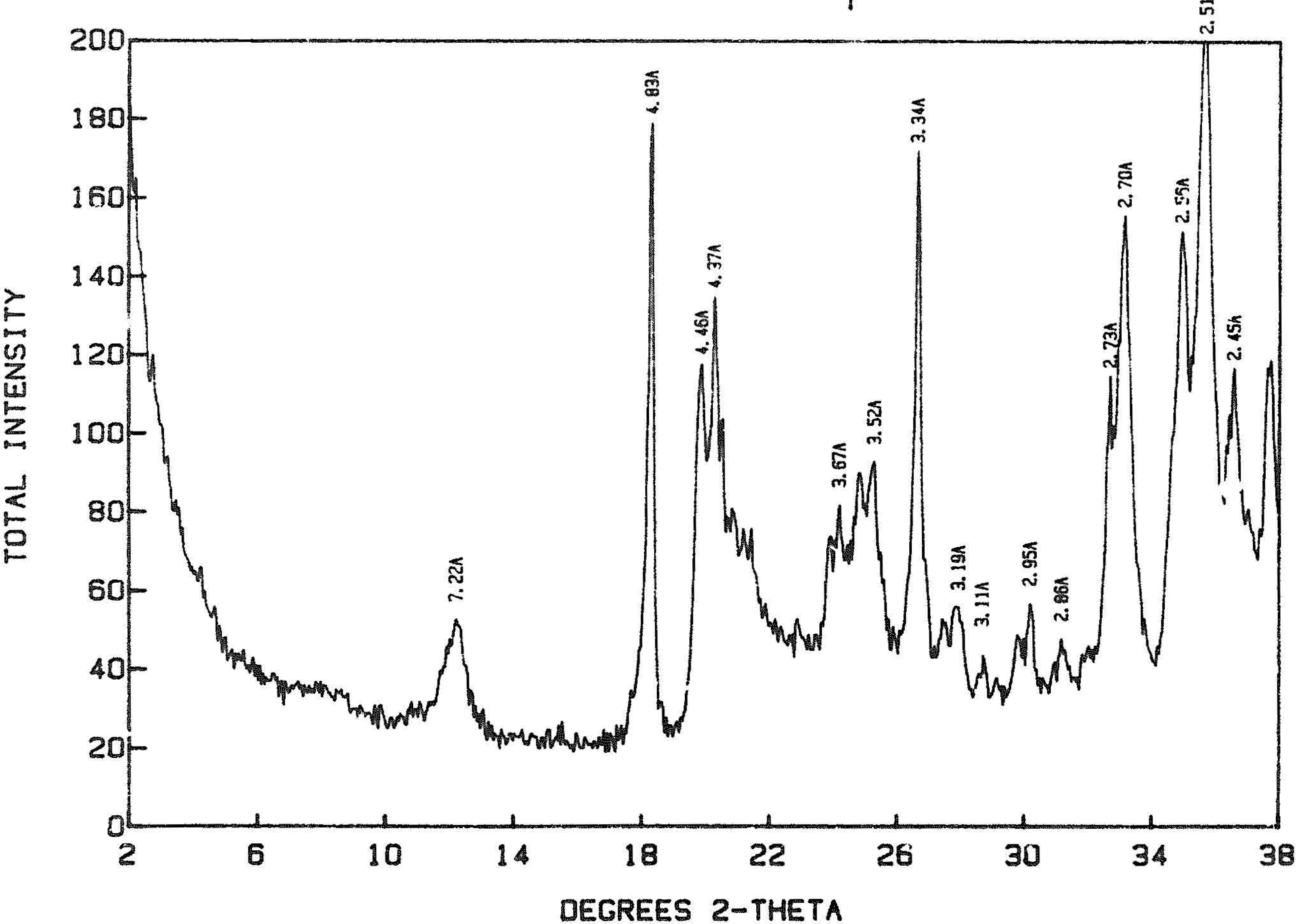
Volume Number 91; File Number D880413.2

SITE 14 3Bt3



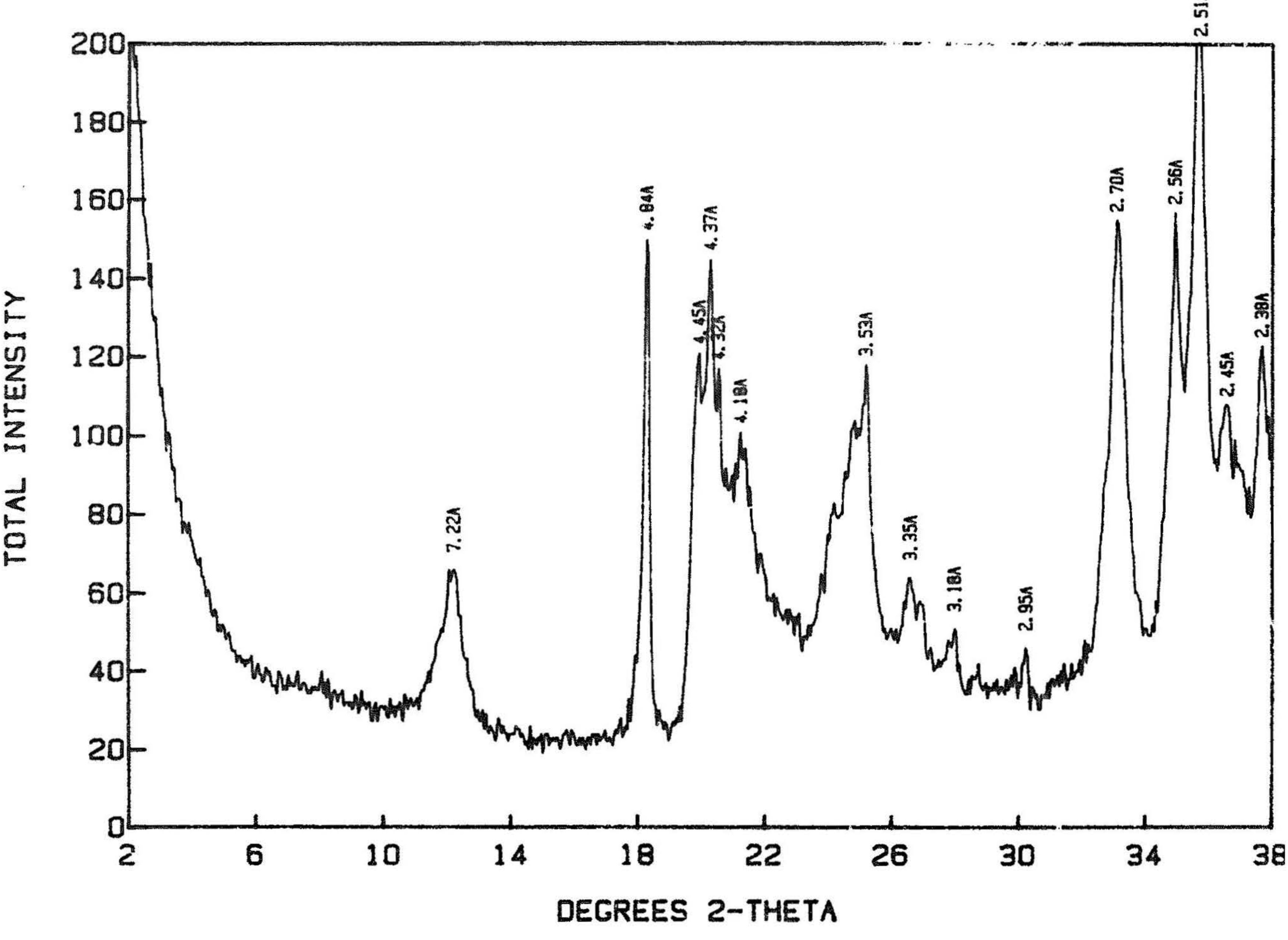
Volume Number 92; File Number D880415.2

SITE 15 Ap1



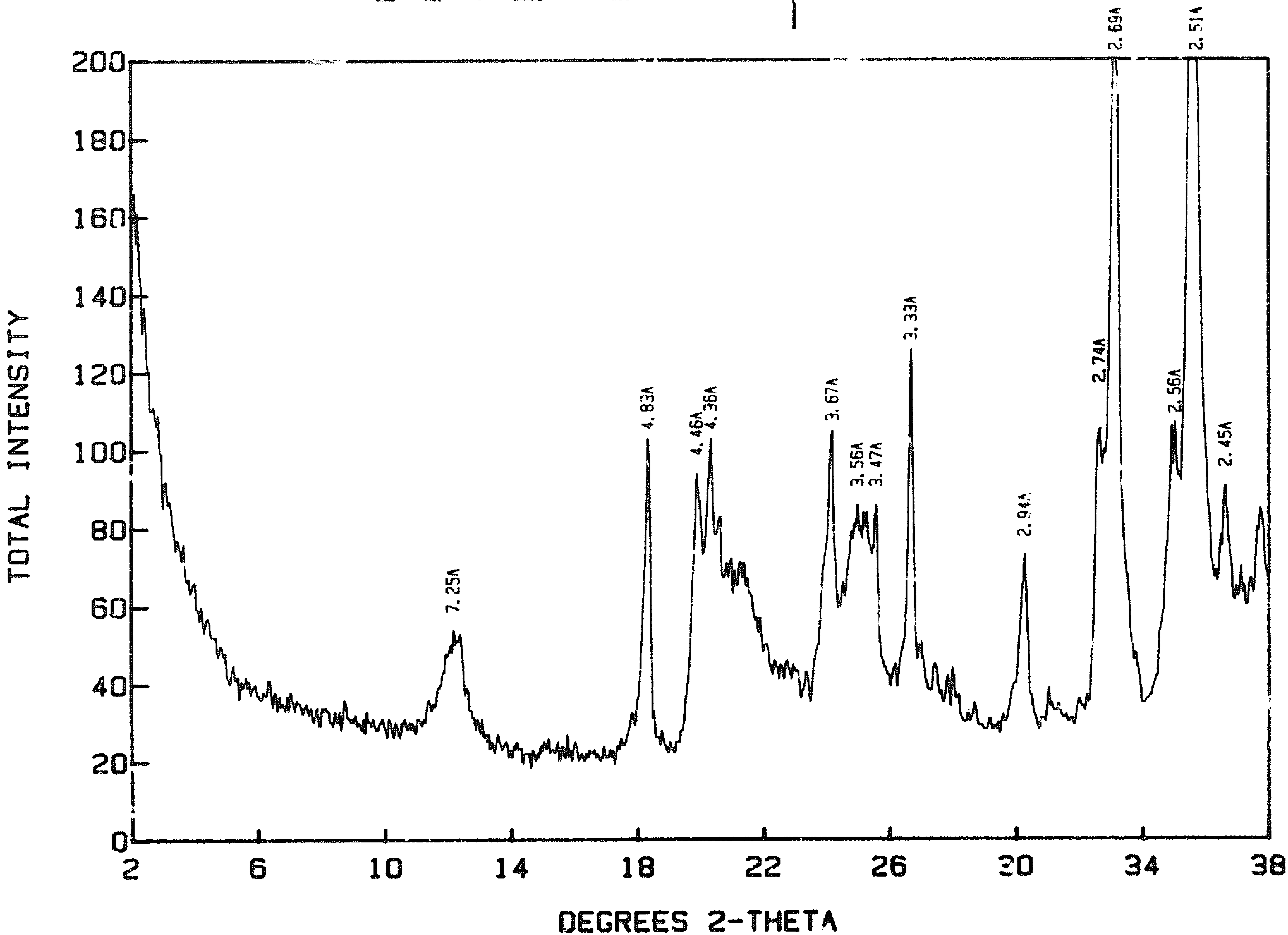
Volume Number 105; File Number D880518.1

SITE 15 Bw3



Volume Number 96; File Number D880424.2

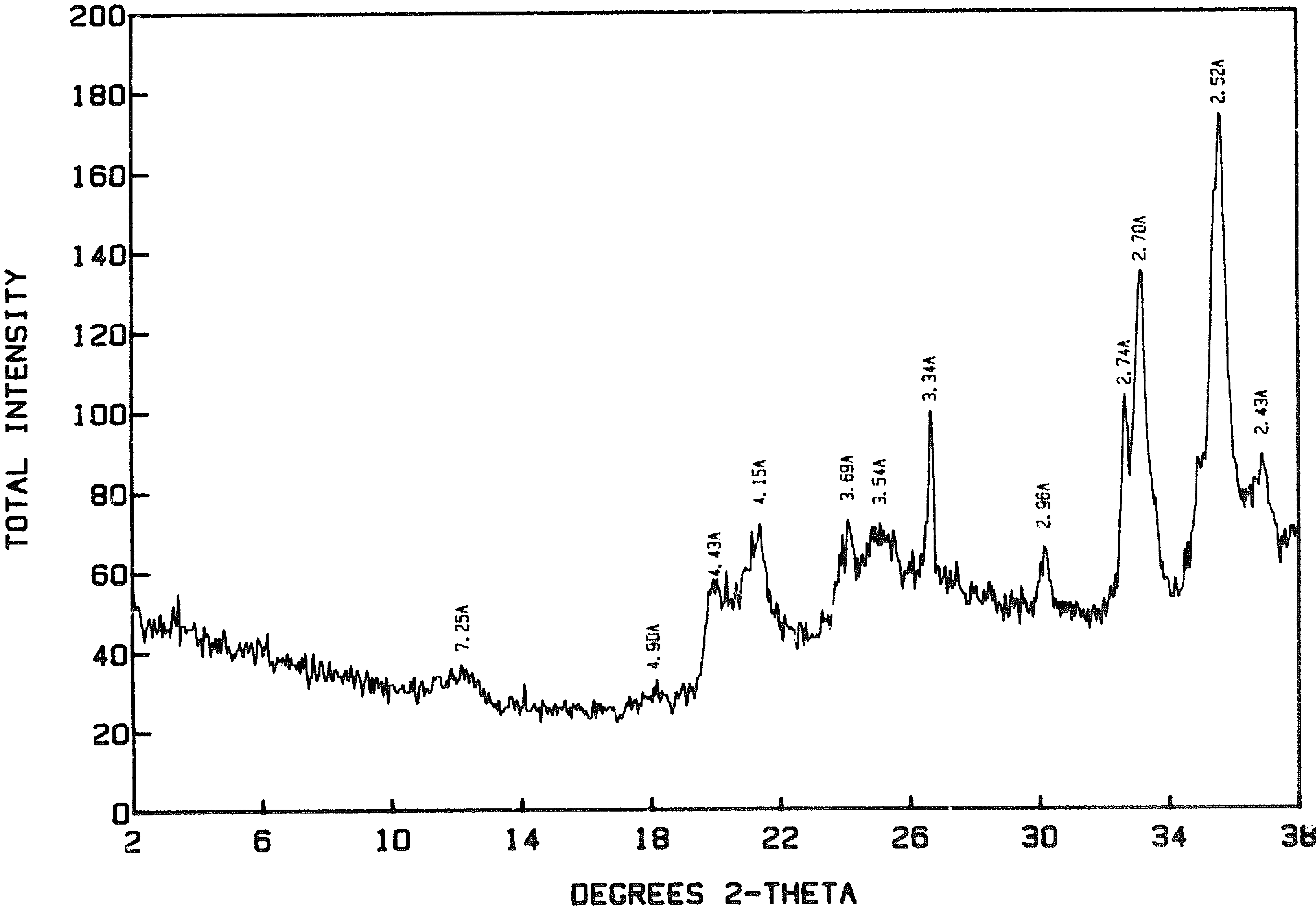
SITE 3 Ap



Volume Number 100; File Number 0880504.7

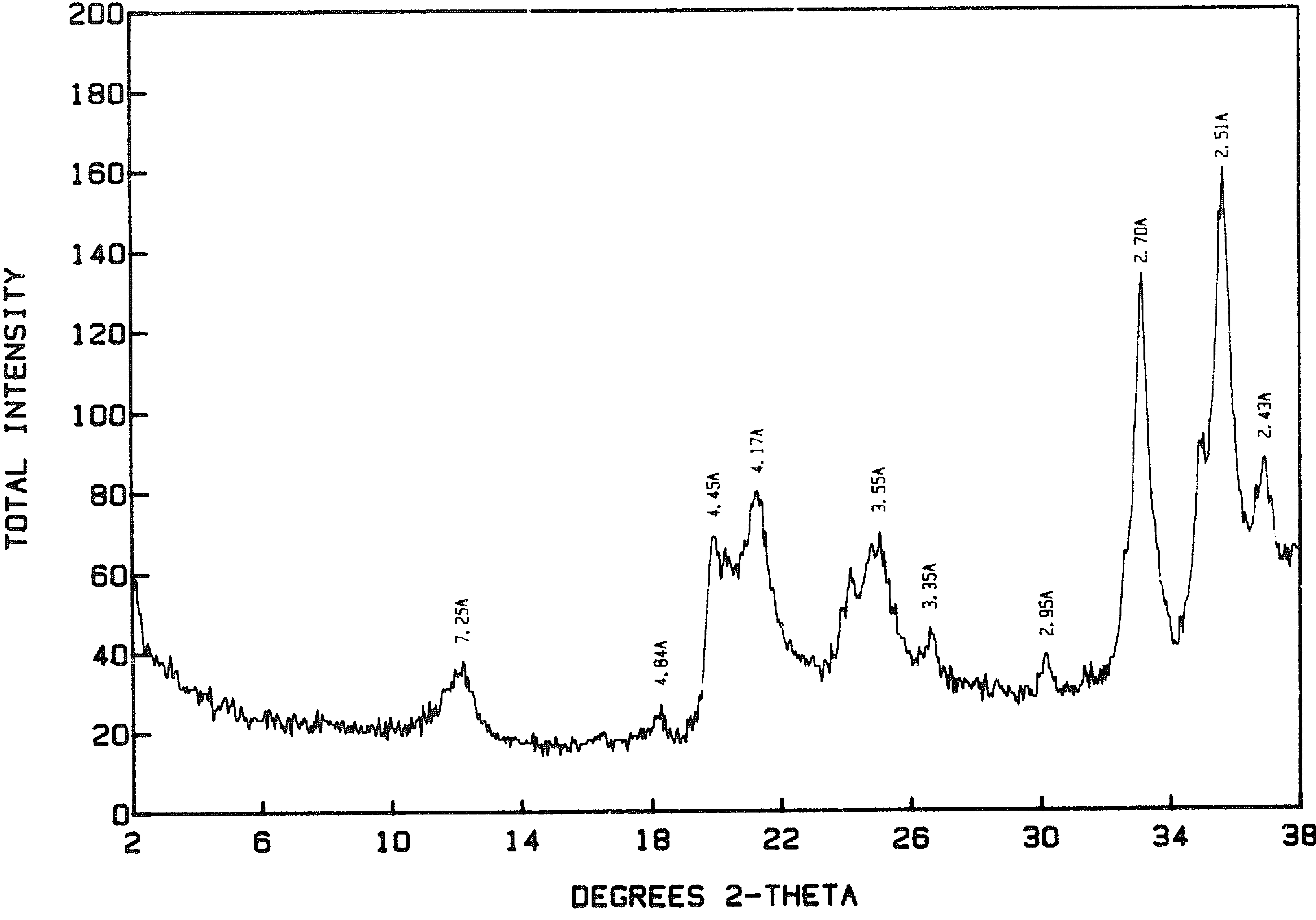
Appendix H. X-ray diffractograms of selected samples from Sites 1 through 20.

SITE 1 Ap



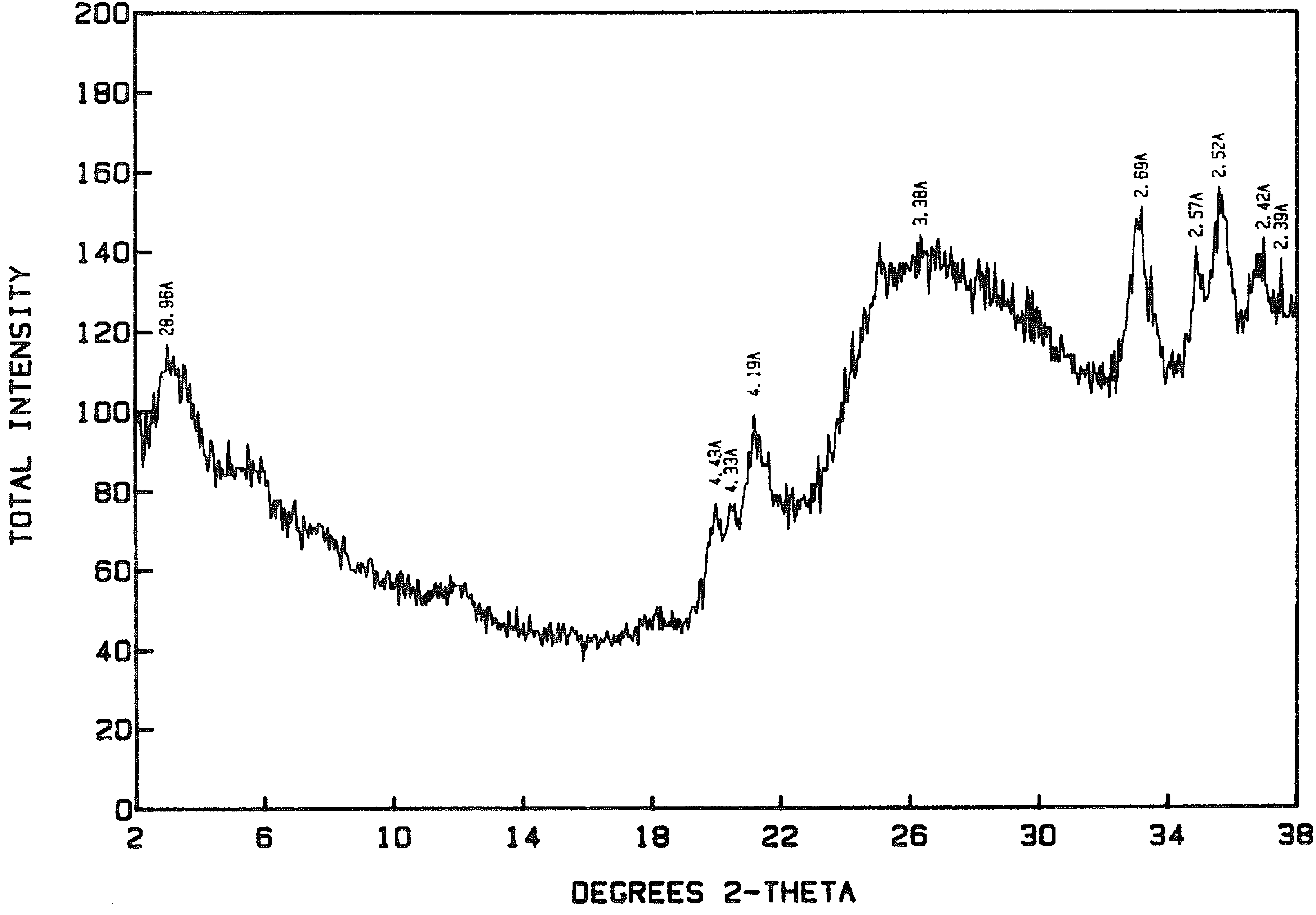
Volume Number 120; File Number D880719.7

SITE 1 Bw1



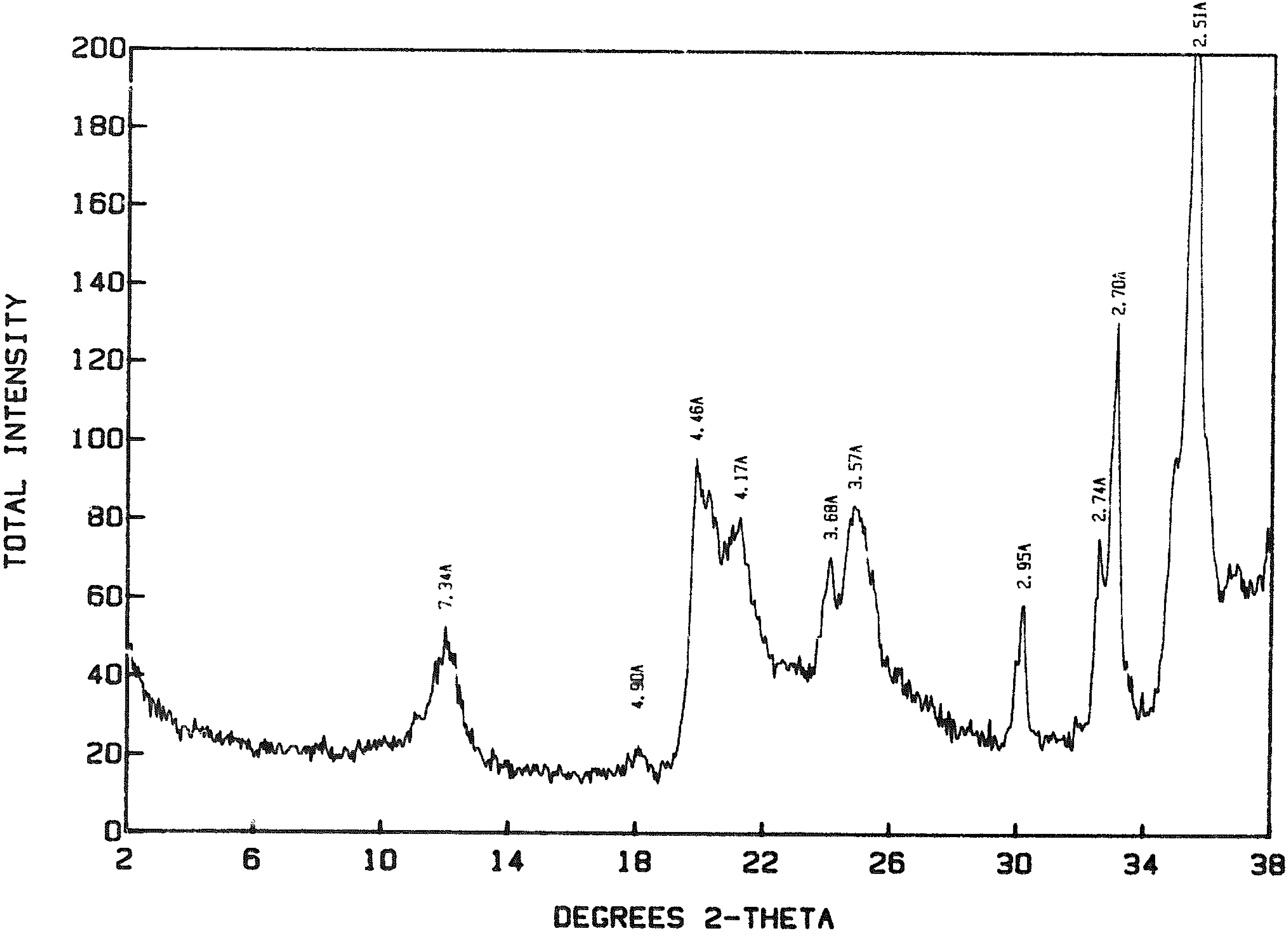
Volume Number 120; File Number D880720.5

SITE 1 Bw4



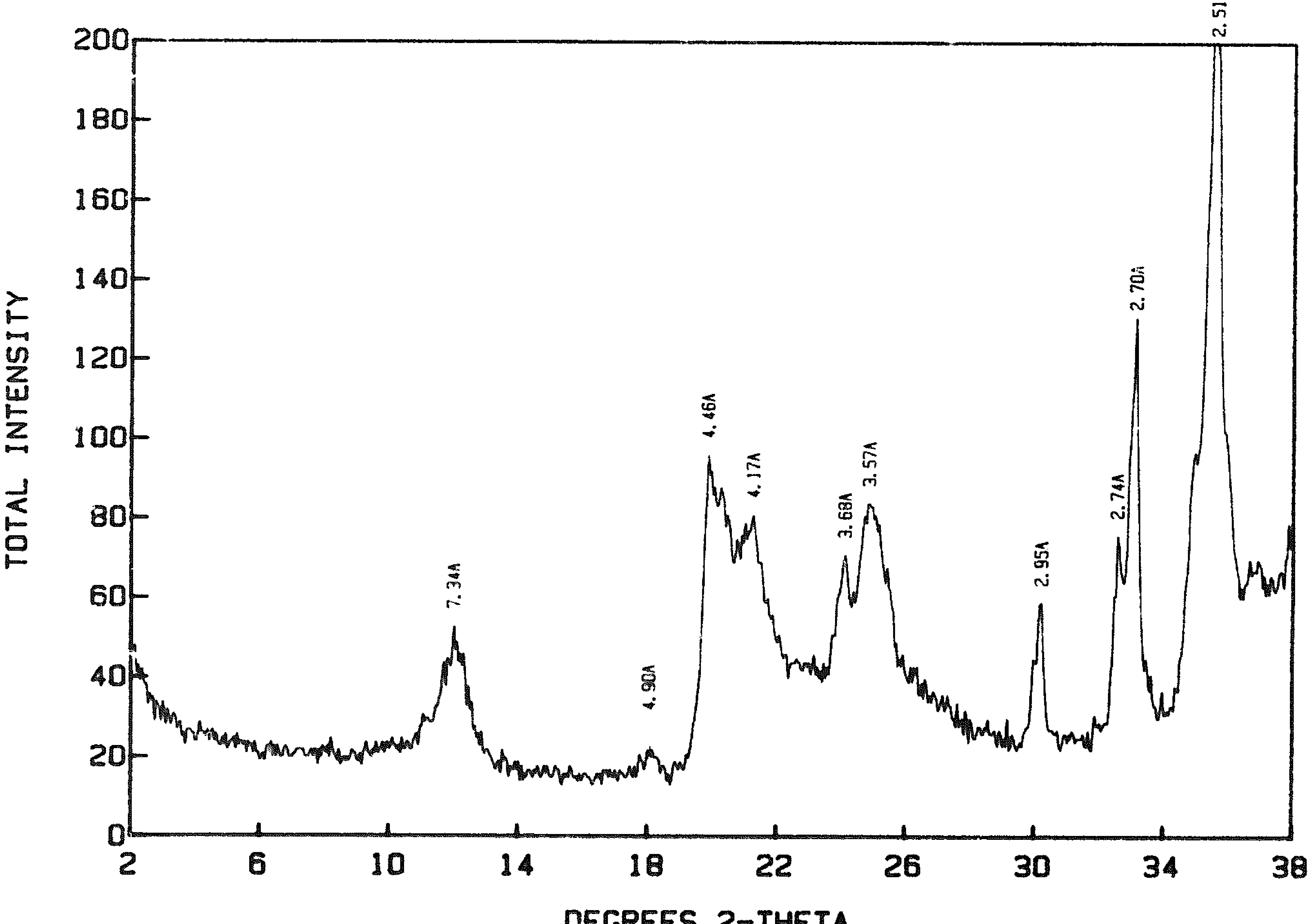
Volume Number 120; File Number D880719.4

SITE 1 2BCt



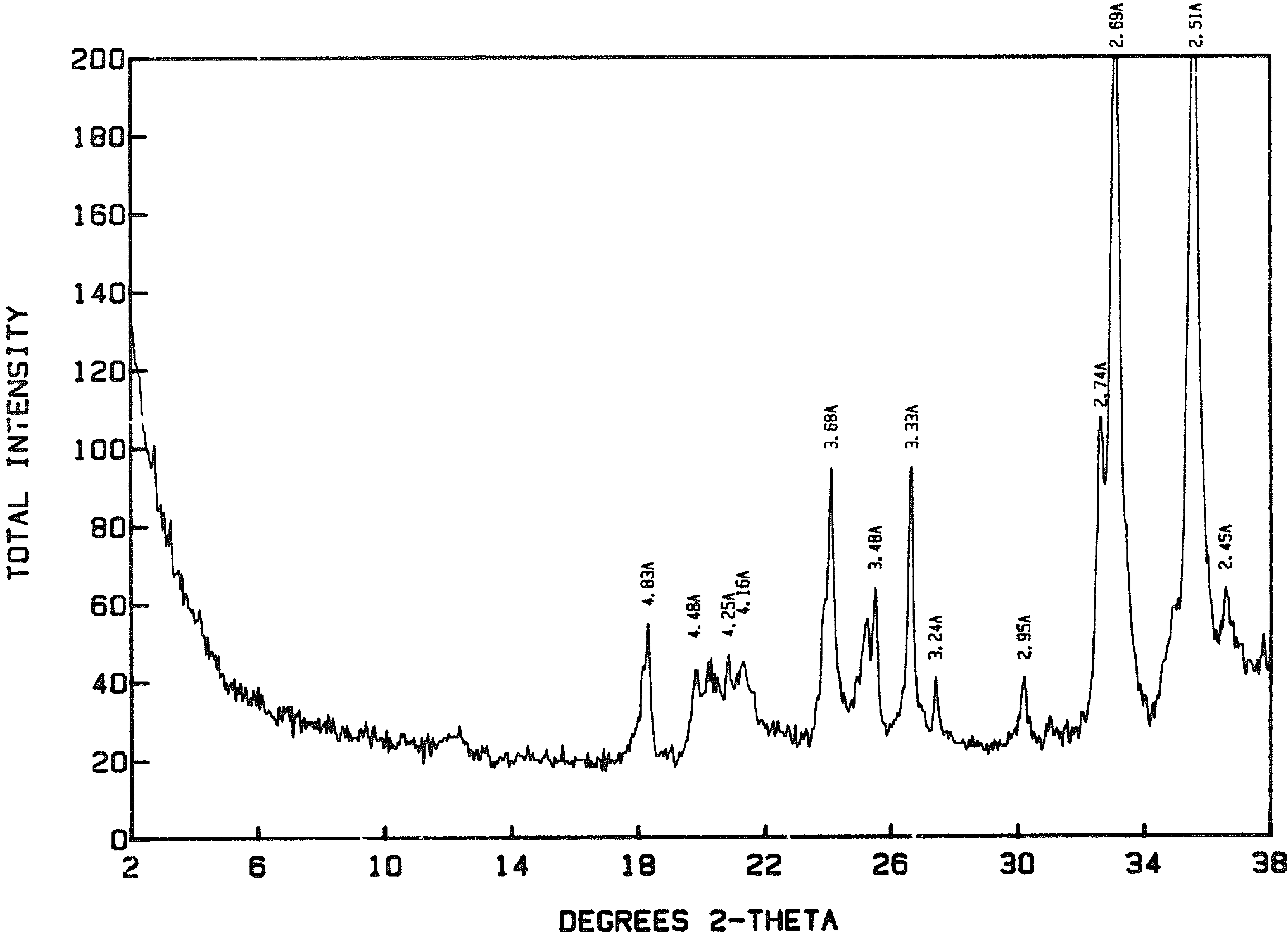
Volume Number 120; File Number D880719.8

SITE 1 2BCt



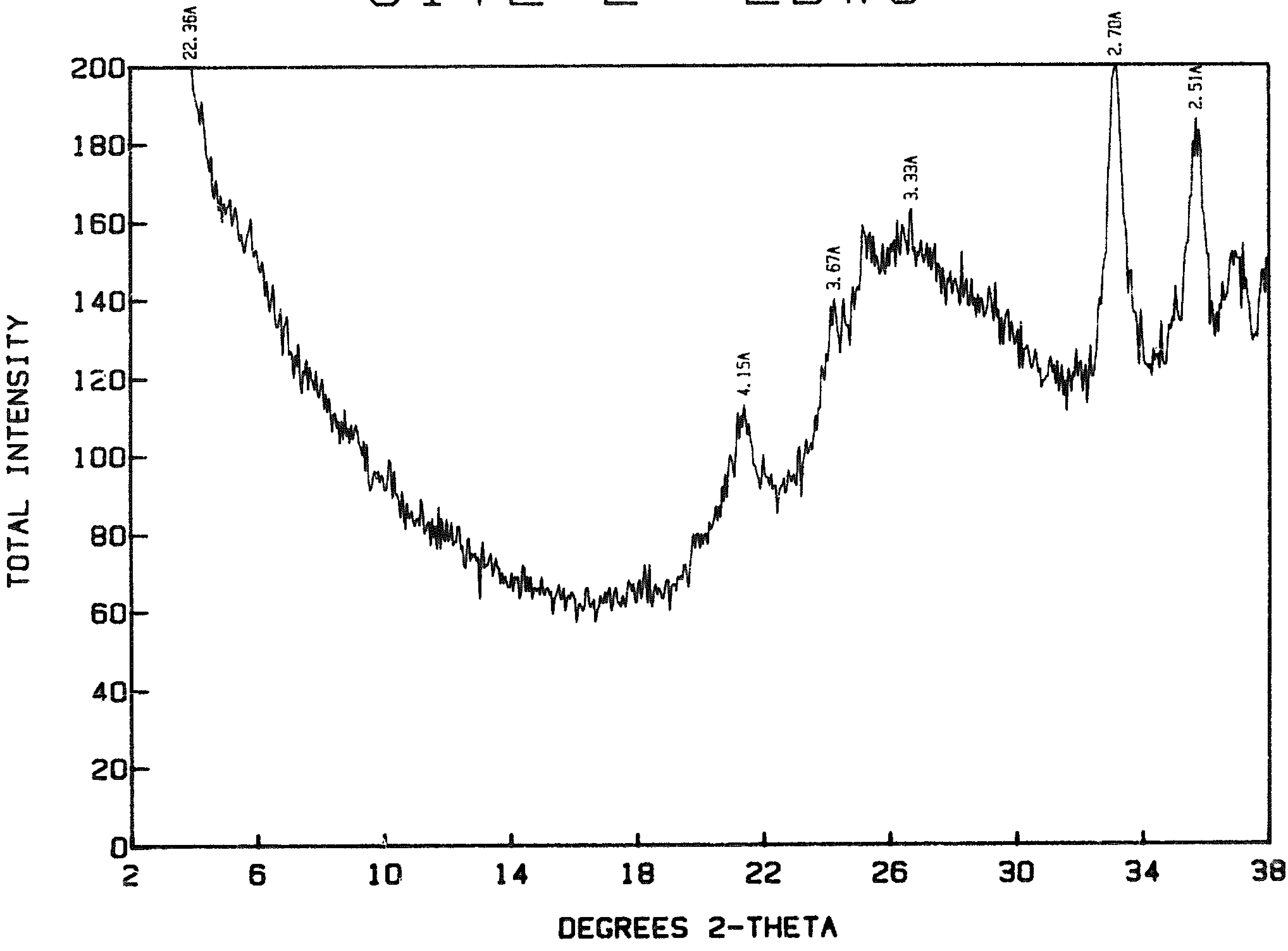
Volume Number 120; File Number 0880719.8

SITE 2 A1



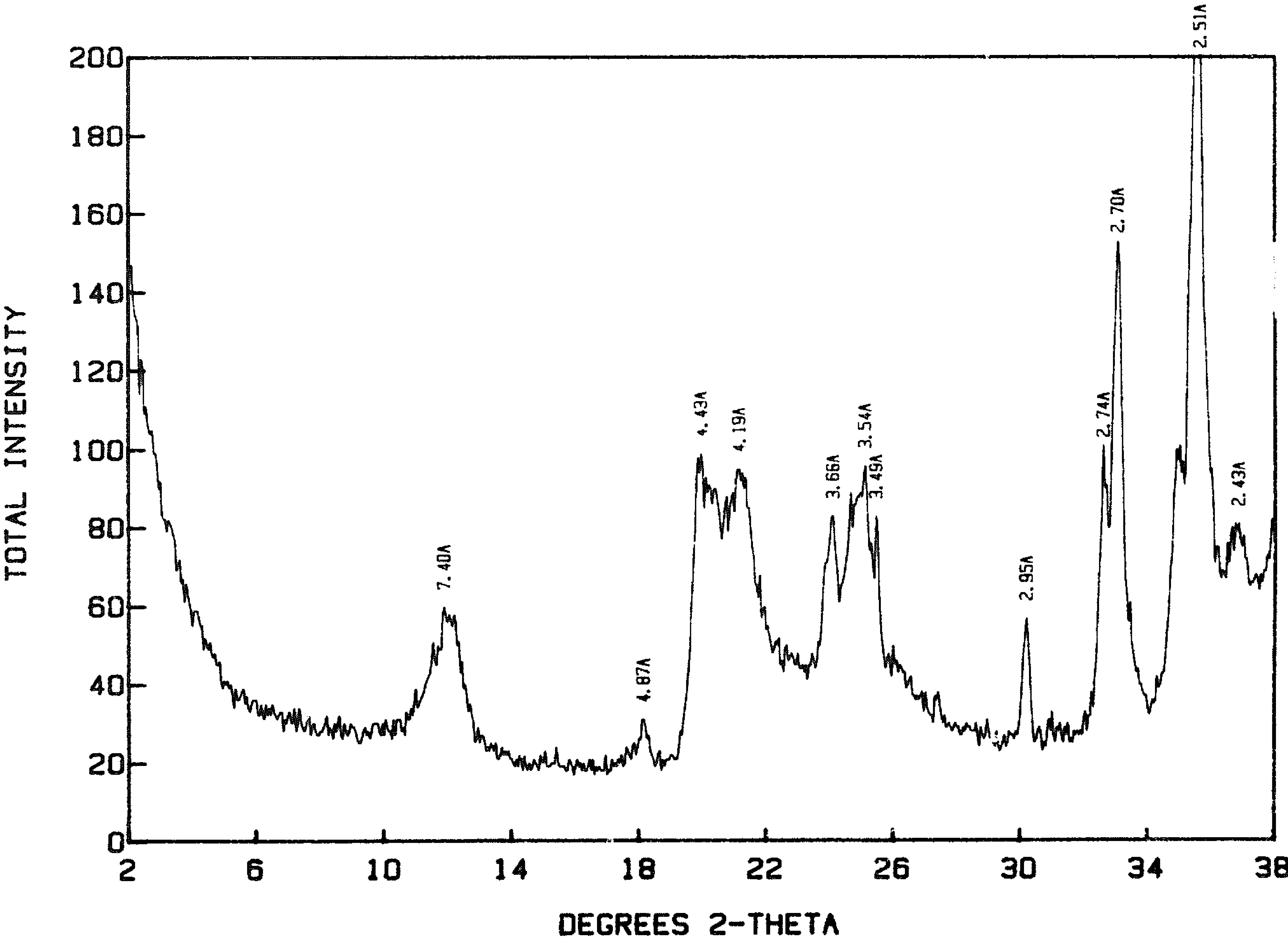
Volume Number 114; File Number D880623.1

SITE 2 2Bw3

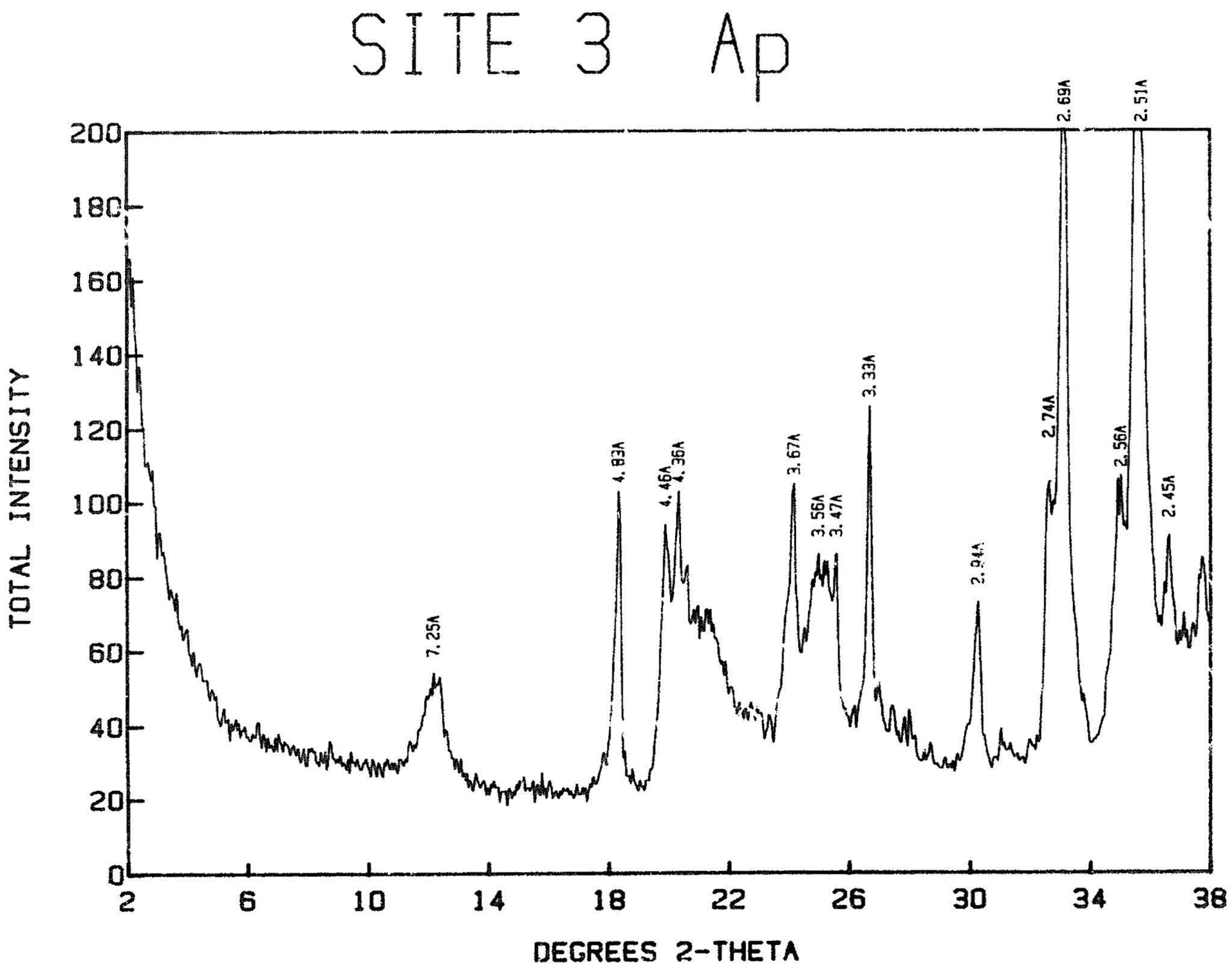


Volu Number 84; File Number D880315.1

SITE 2 3BCT2

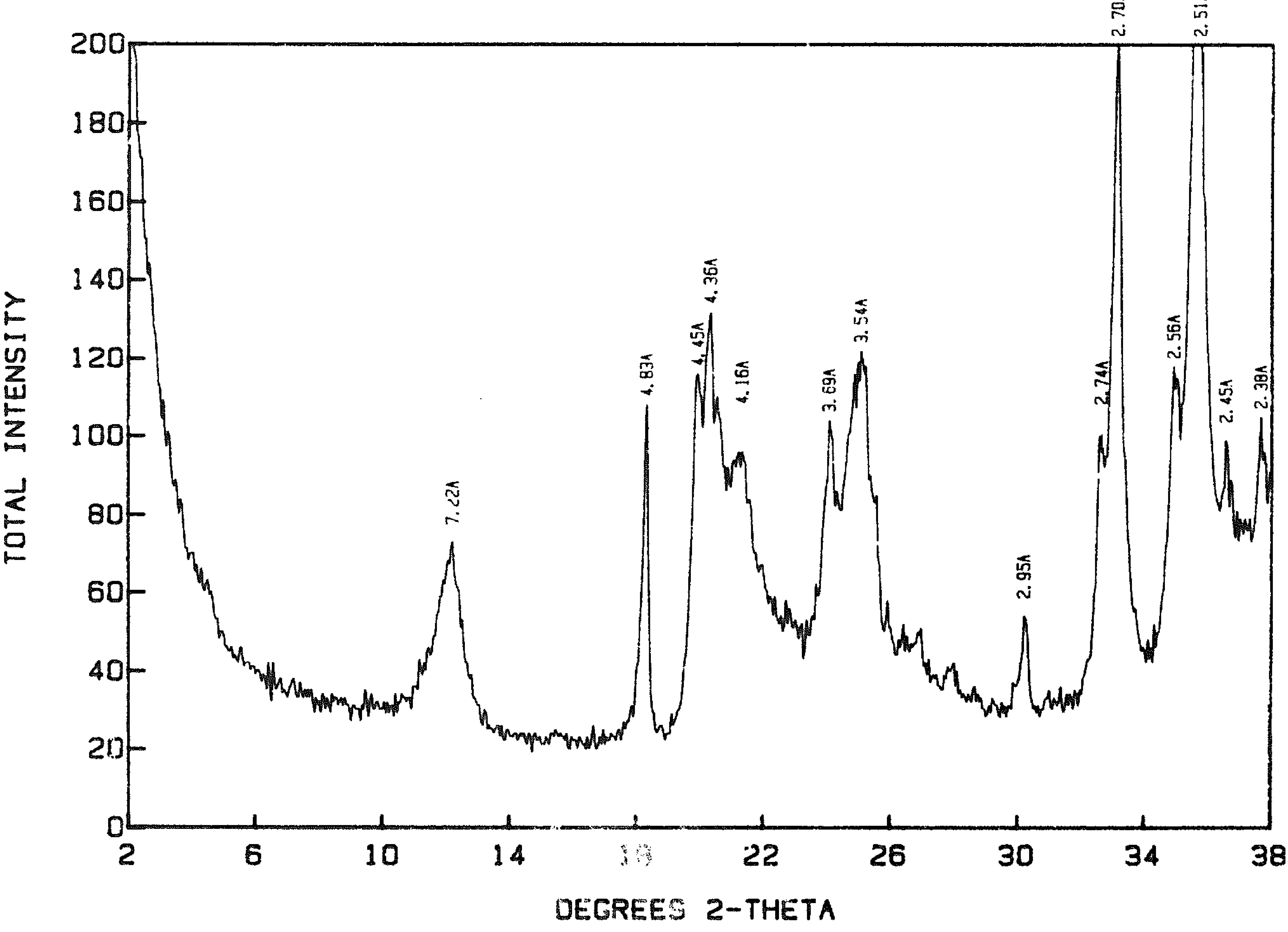


Volume Number 117; File Number D880703.2



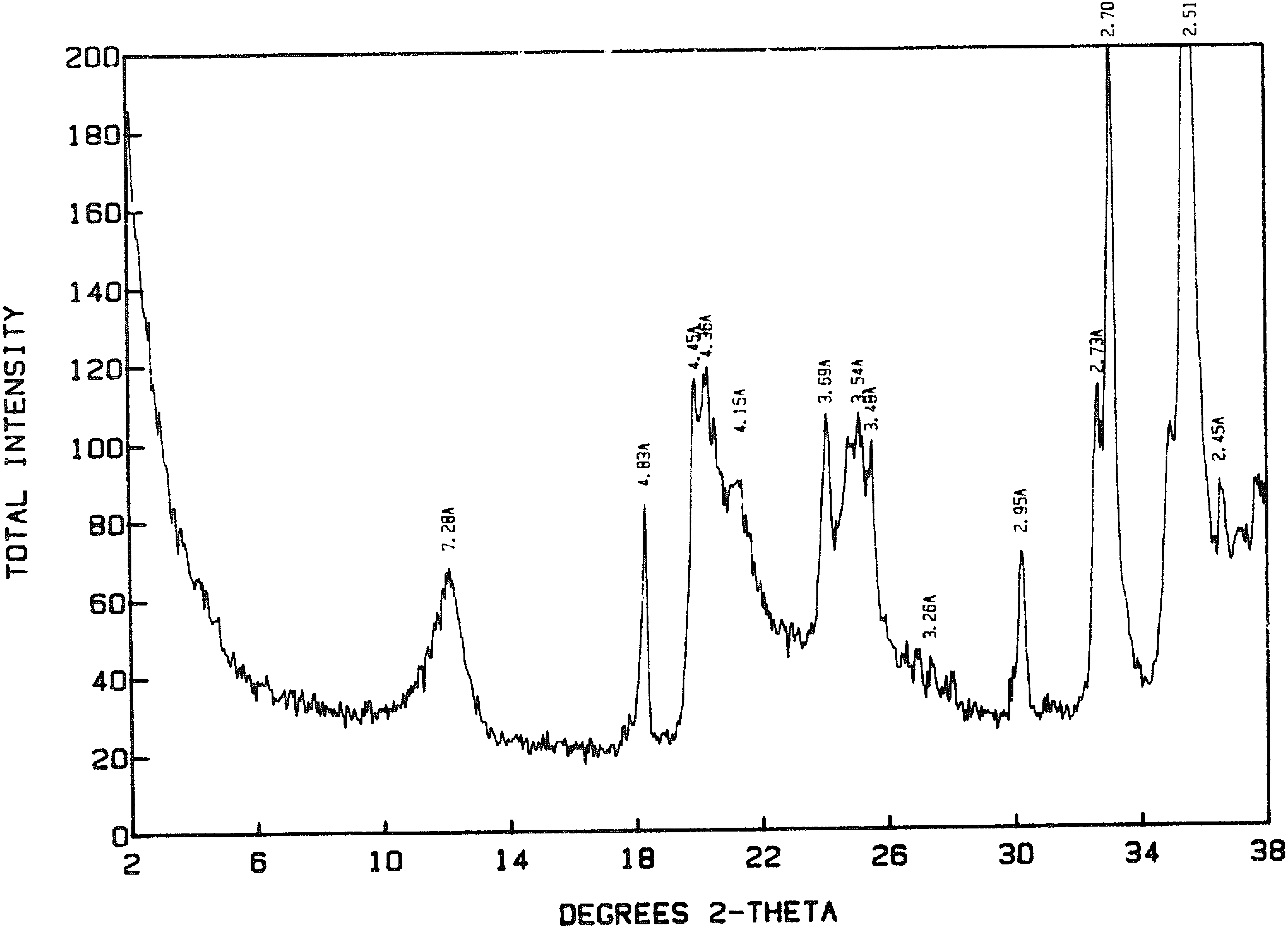
Volume Number 100; File Number D880504.7

SITE 3 Bw2



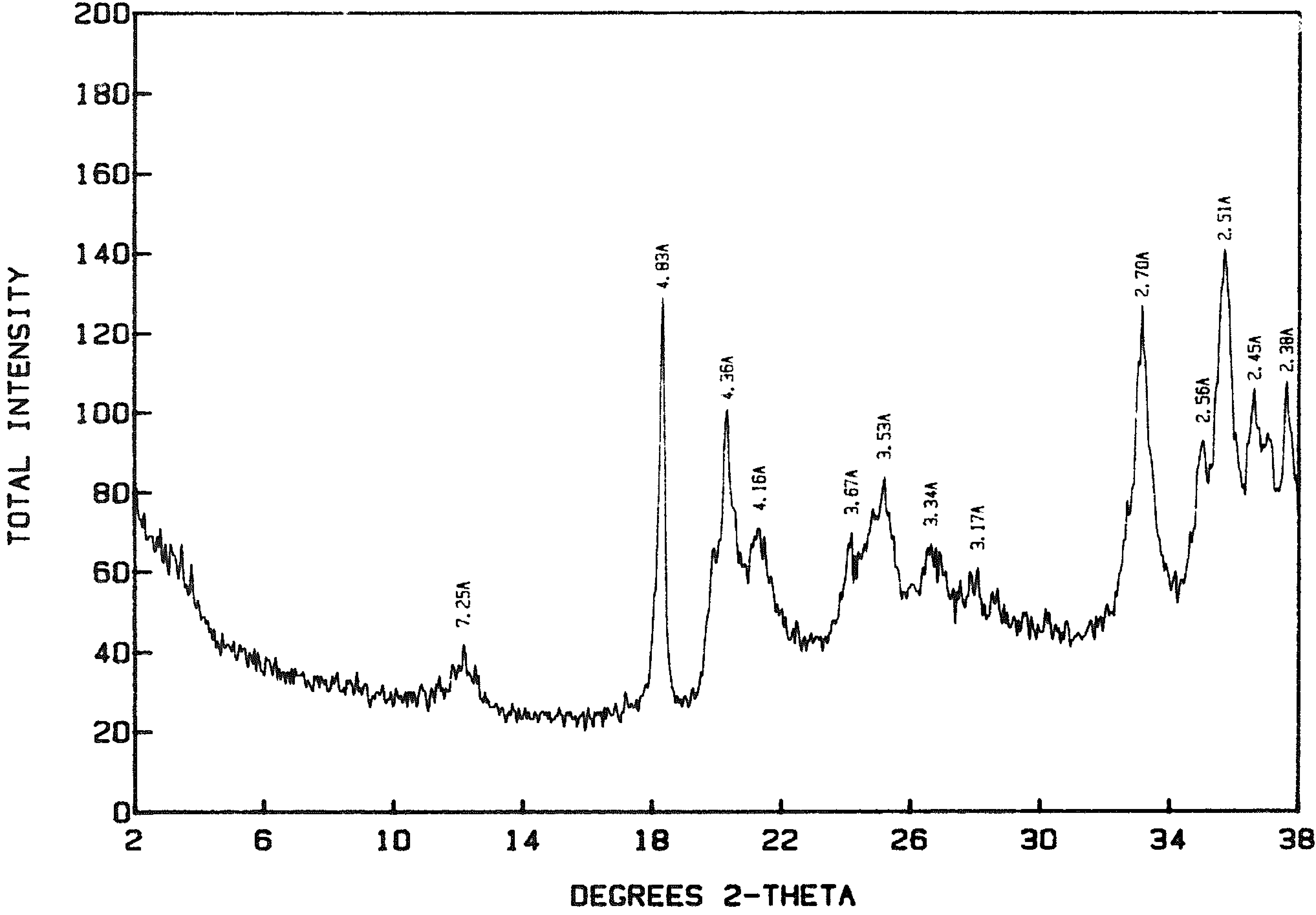
Volume Number 99; File Number D880502.3

SITE 3 2Bt



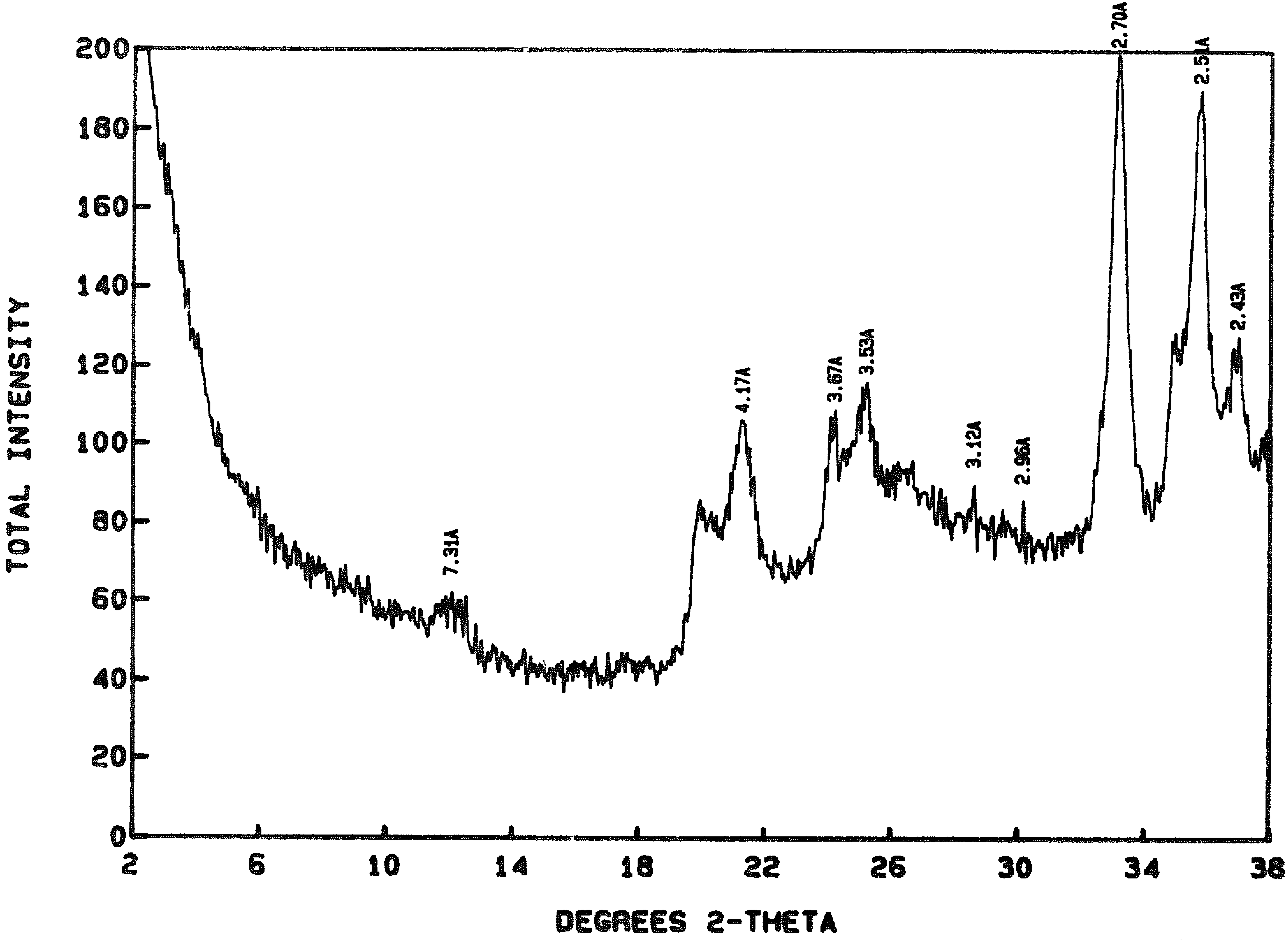
Volume Number 99; File Number D880503.4

SITE 3b Bw2



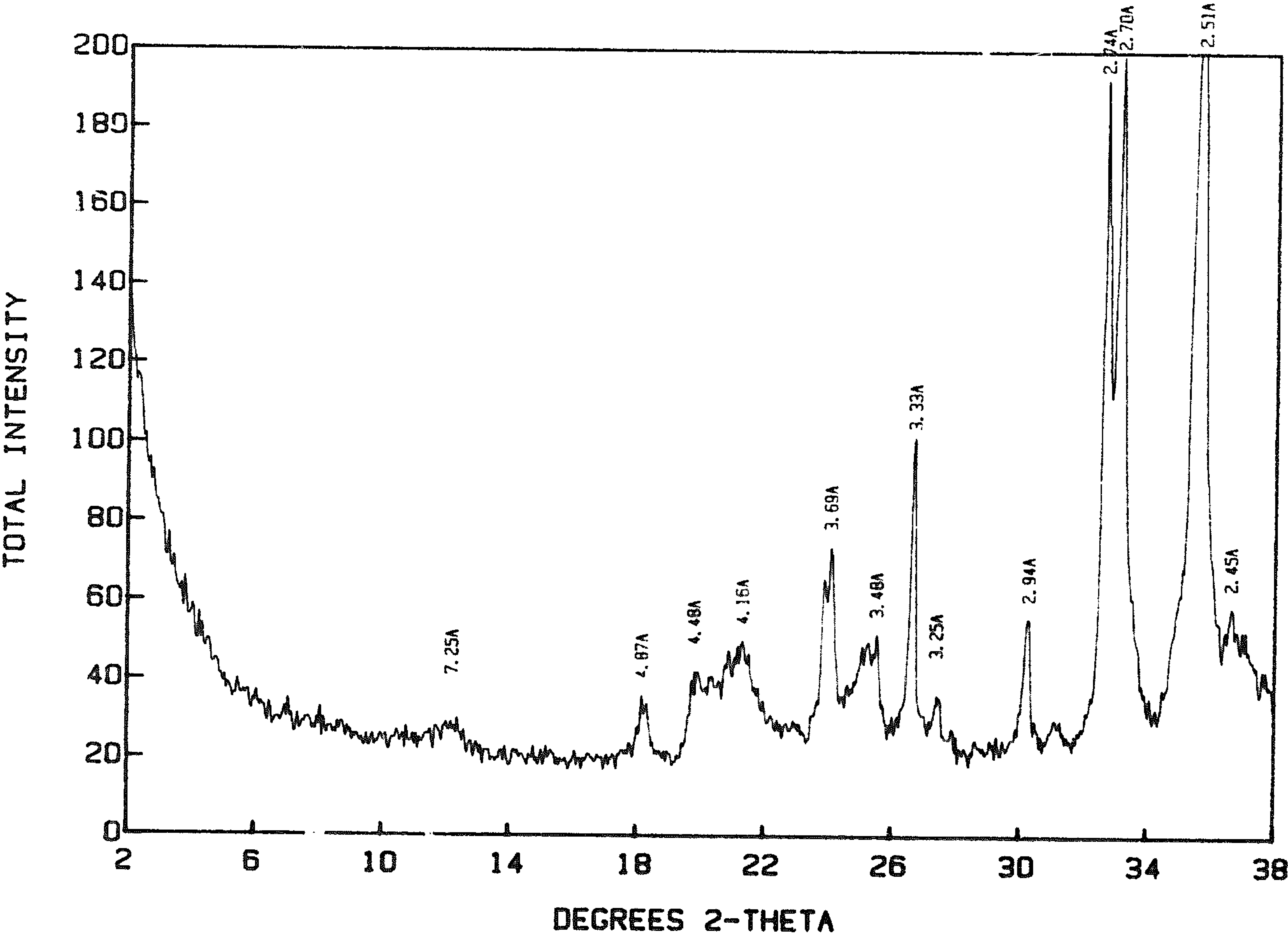
Volume Number 119; File Number 0880718.1

SITE 3C Bw

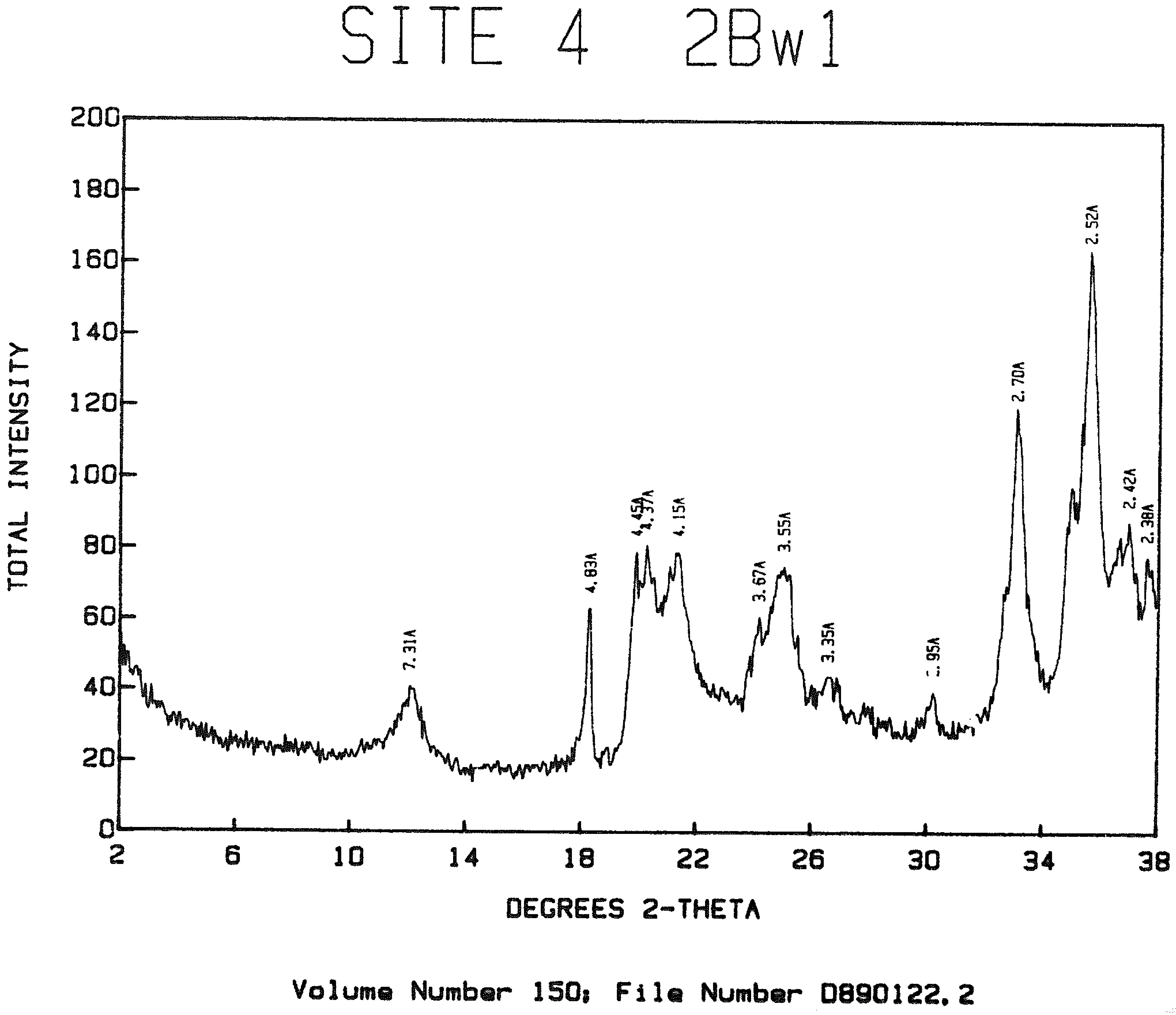


Volume Number 95: File Number D880422.6

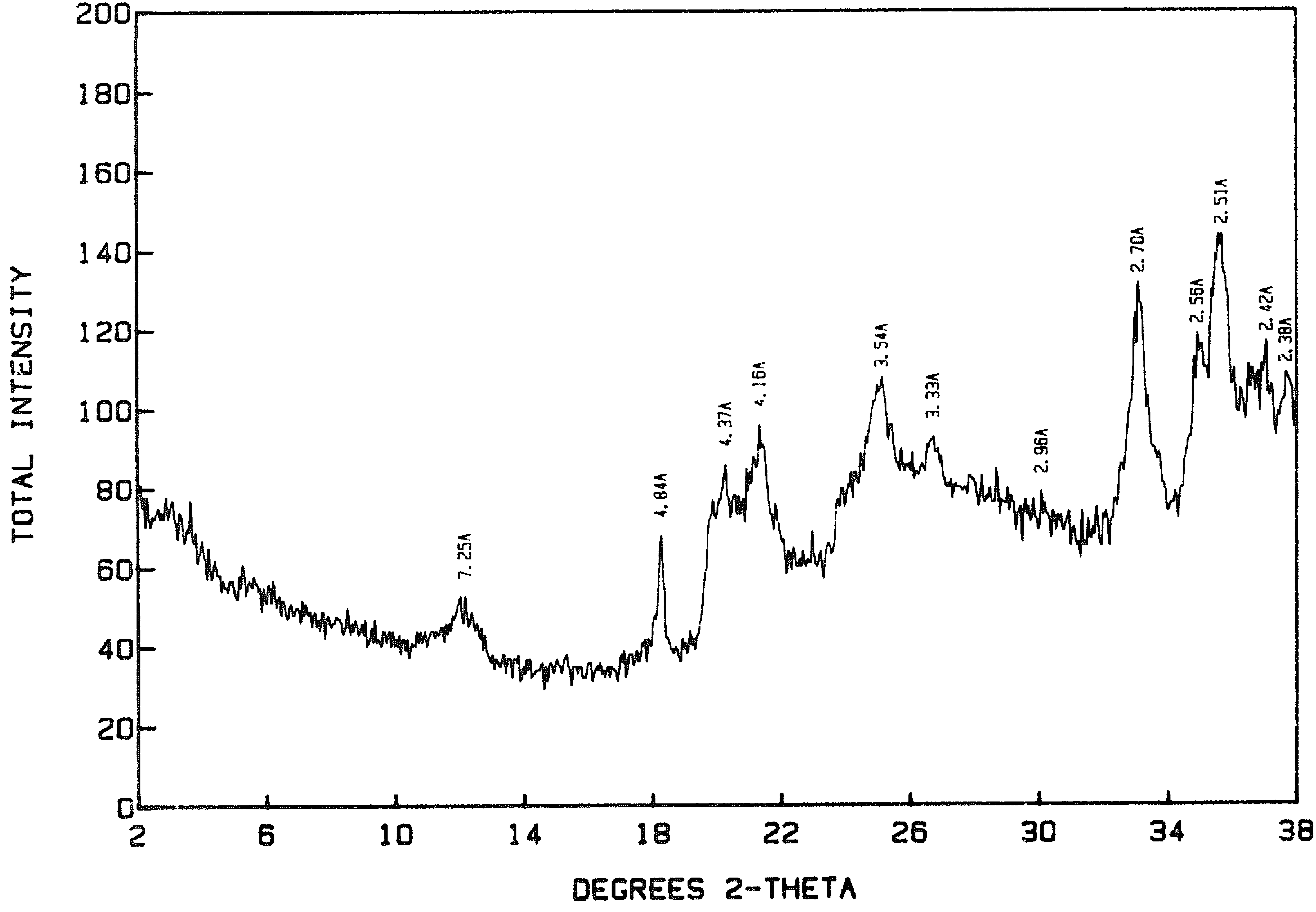
SITE 4 A



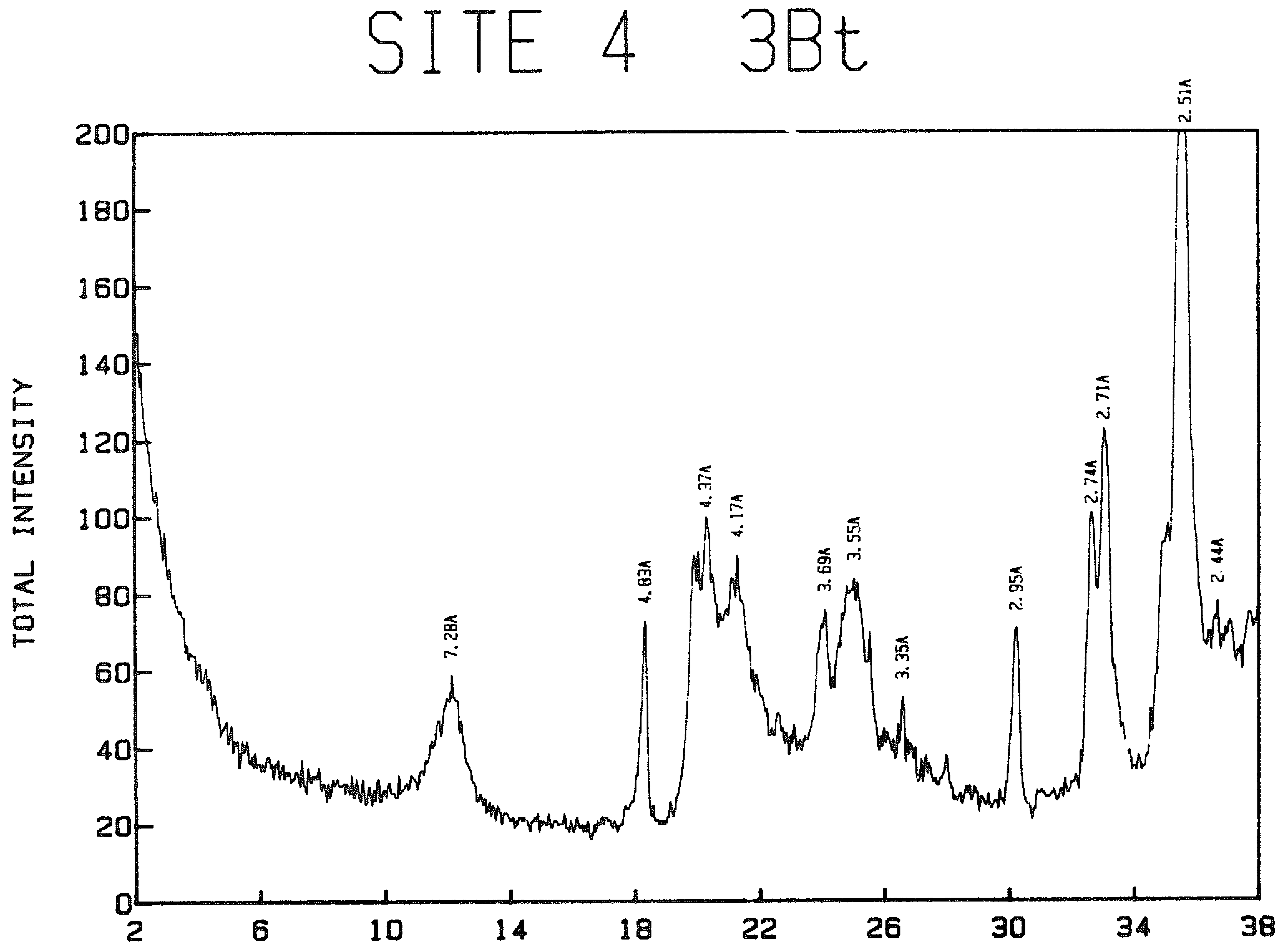
Volume Number 116; File Number D880629.6


SITE 4 2Bw1
TOTAL INTENSITY
DEGREES 2-THETA
0
20
40
60
80
100
120
140
160
180
200
2
6
10
14
18
22
26
30
34
38
7.31A
4.83A
4.45A
4.37A
4.15A
3.67A
3.55A
3.35A
2.70A
2.52A
2.42A
2.38A
Volume Number 150; File Number D890122.2

SITE 4 2Bw2

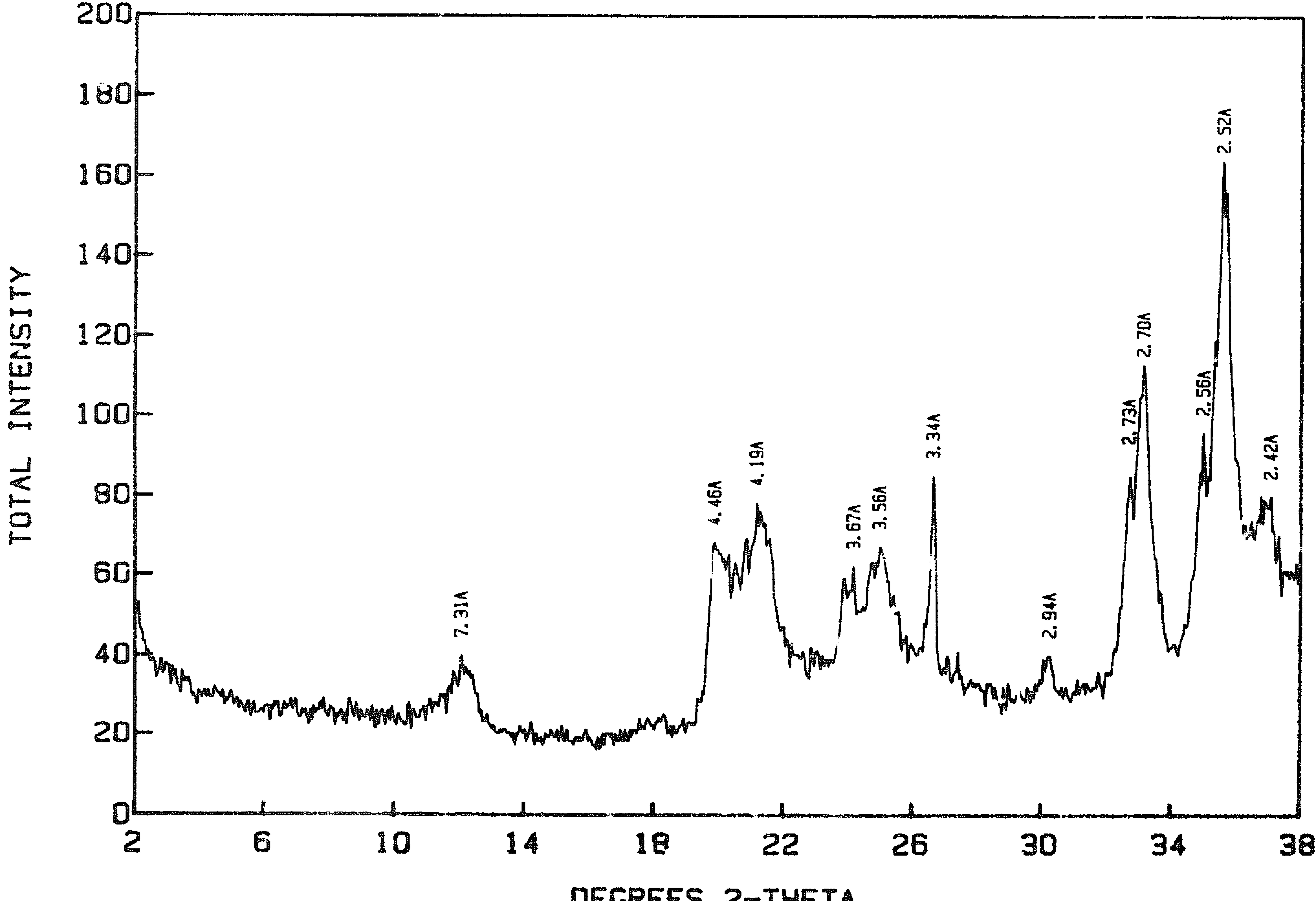


Volume Number 150; File Number D890122.1



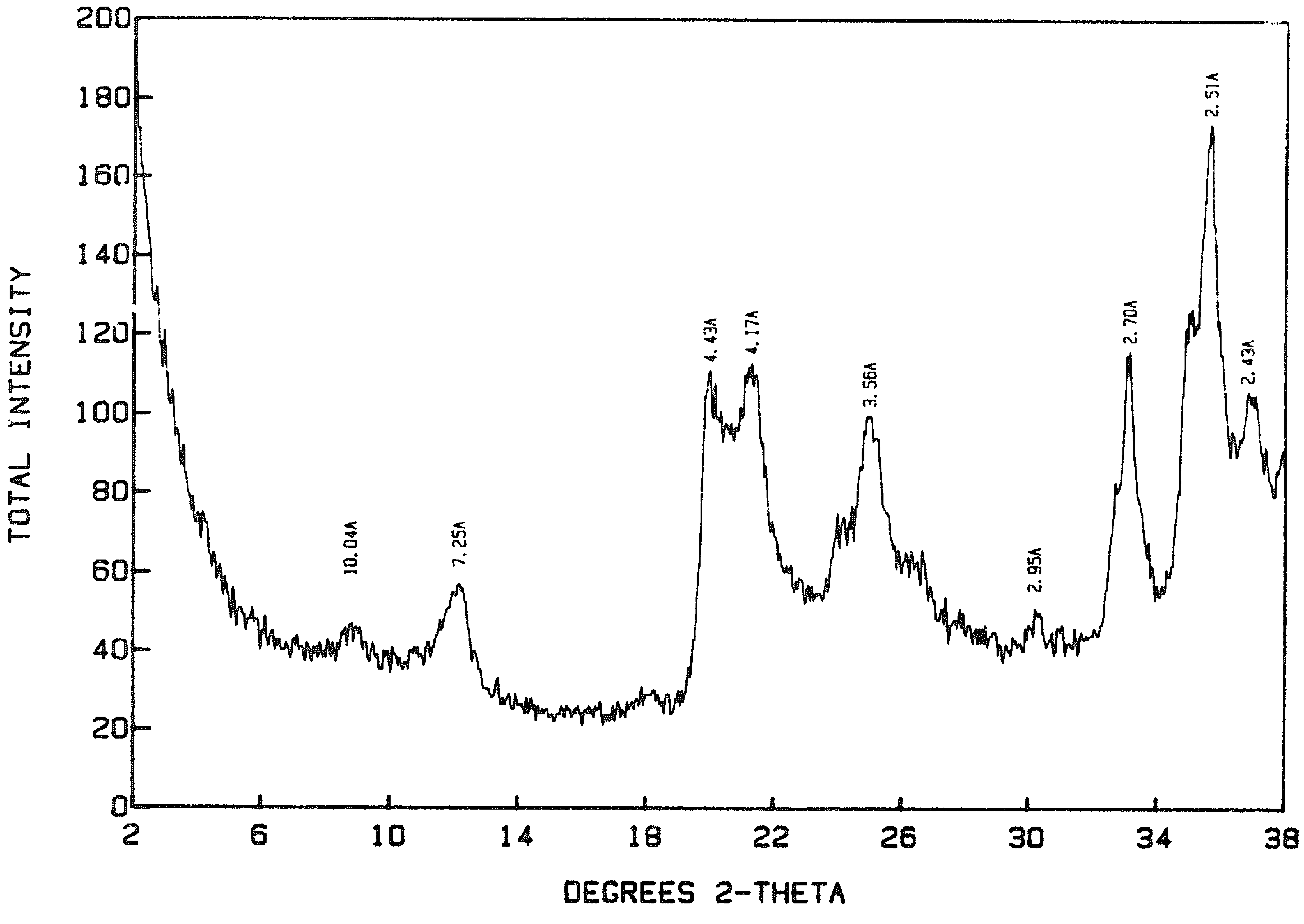
Volume Number 116; File Number D880630.1

SITE 5 A



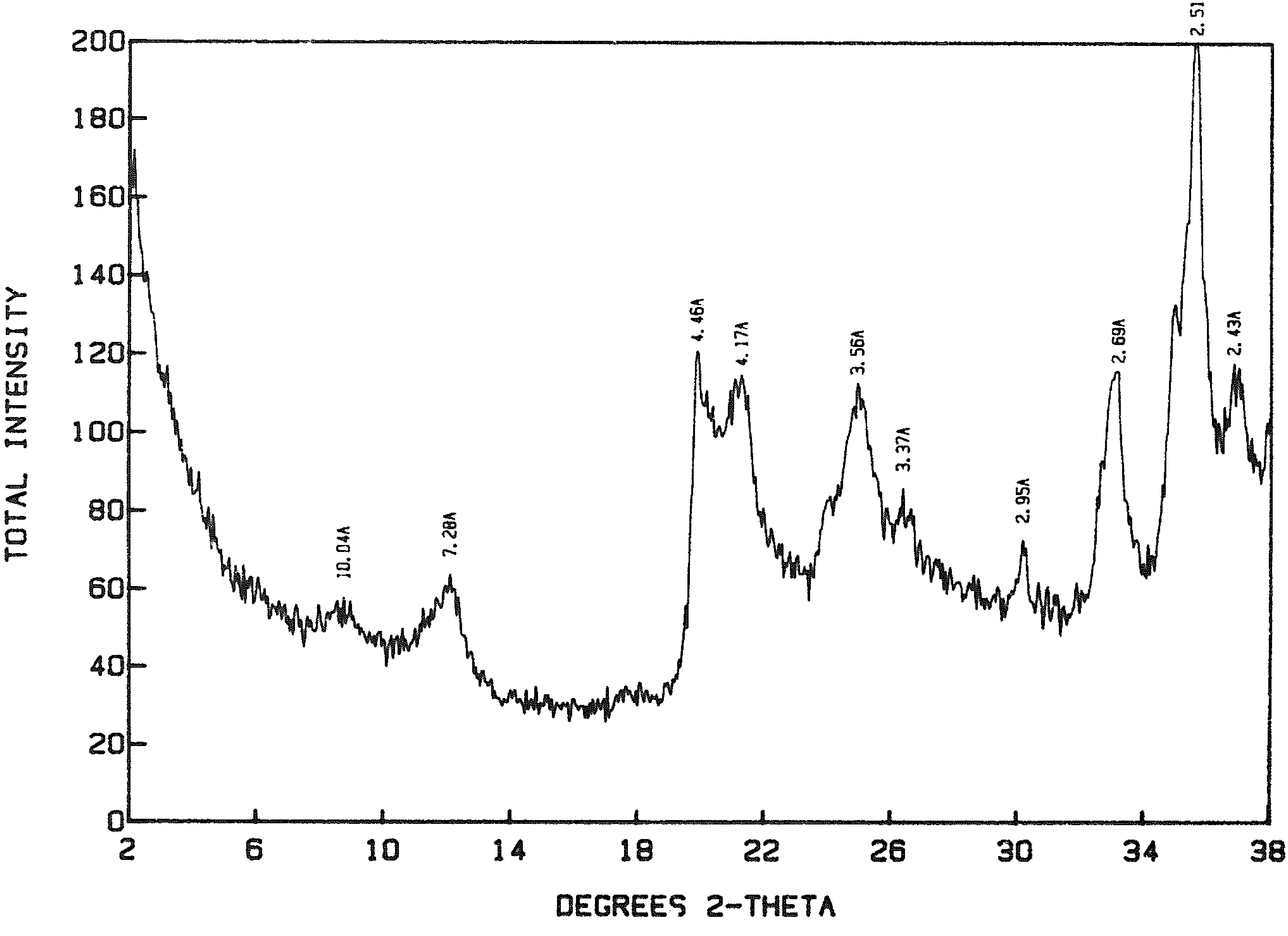
Volume Number 150; File Number D890122.3

SITE 5 2Bw1



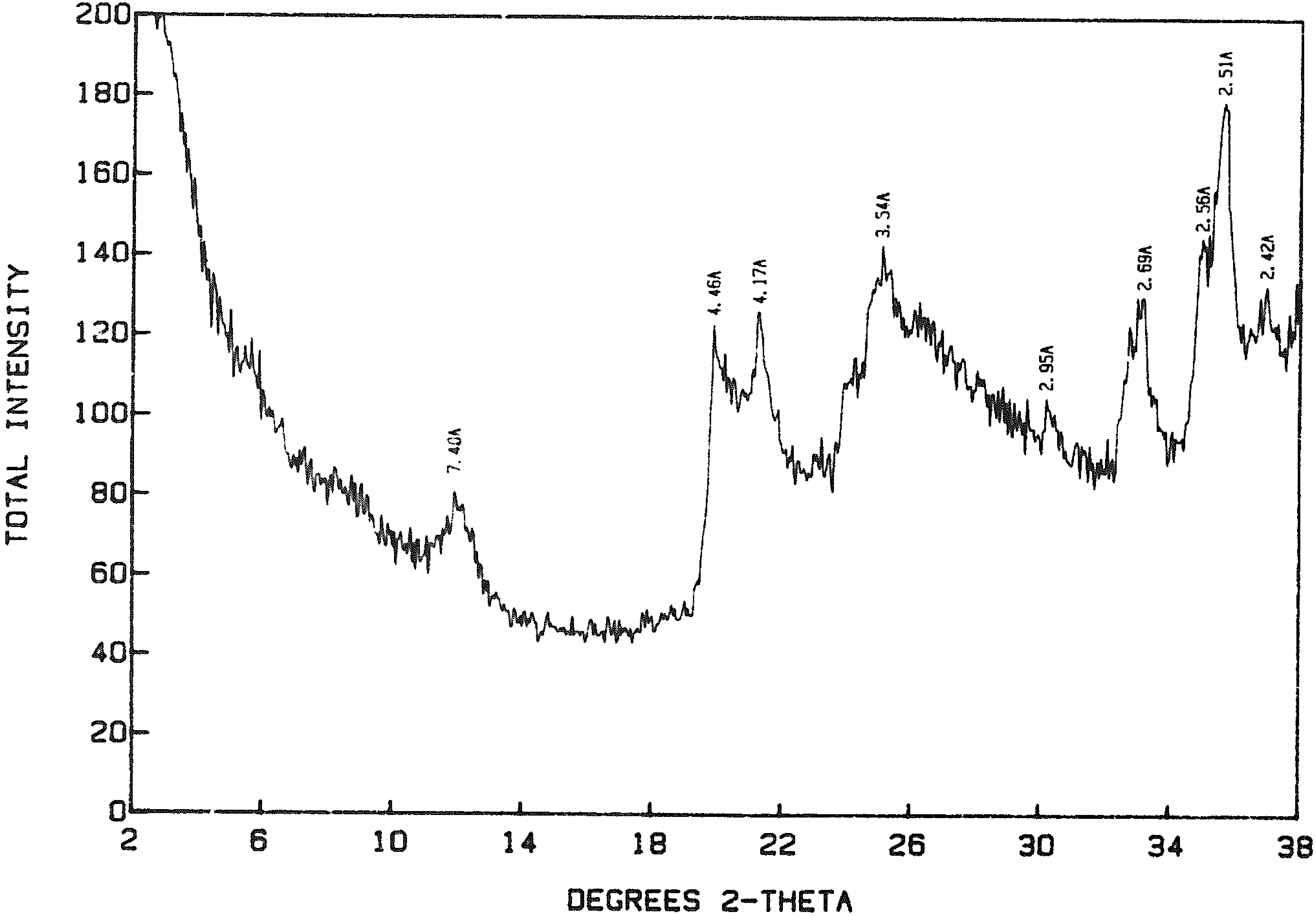
Volume Number 116; File Number D880630.4

SITE 5 2Bw2



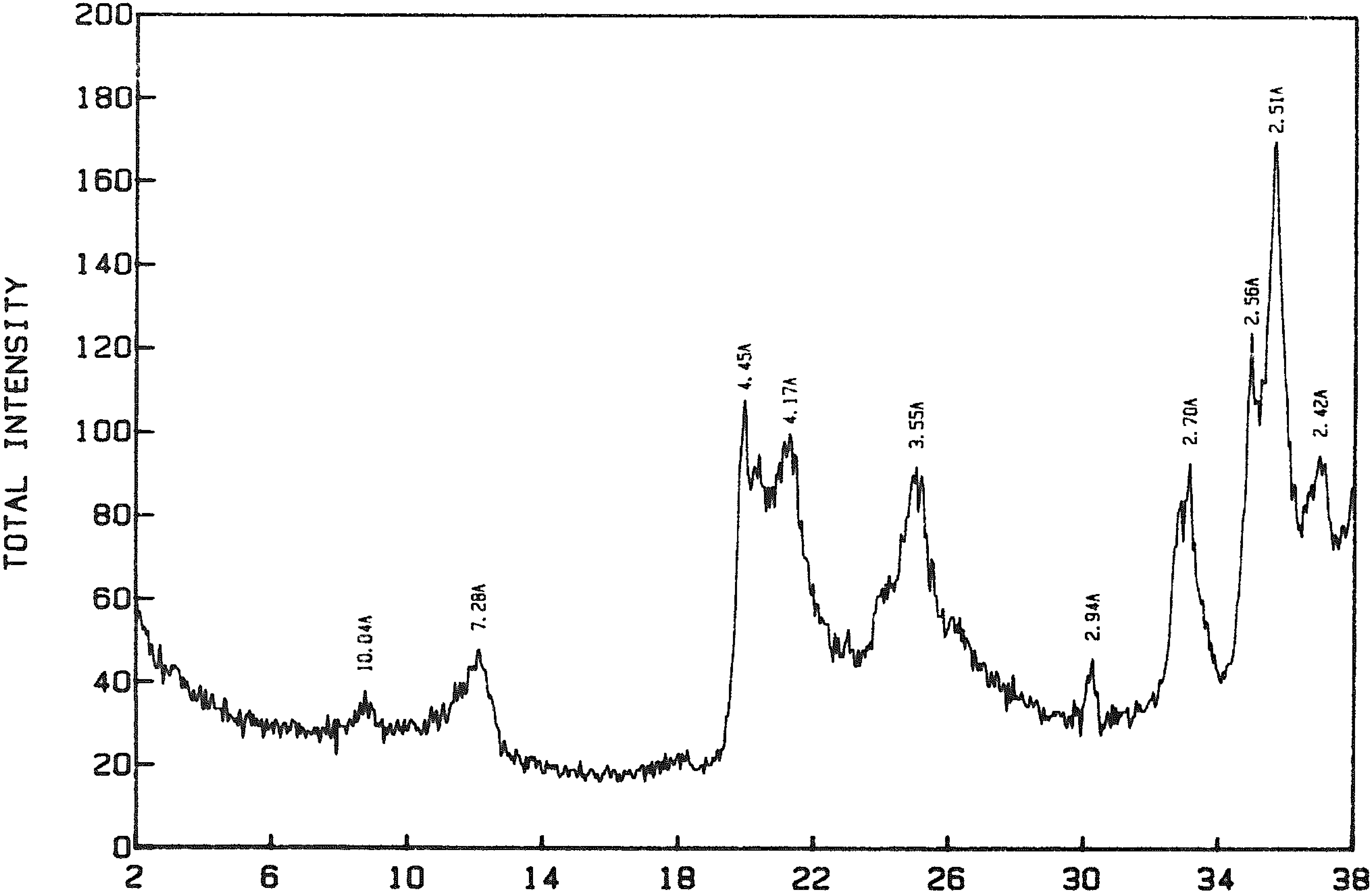
Volume Number 116; File Number D880630.3

SITE 5 2Bw3



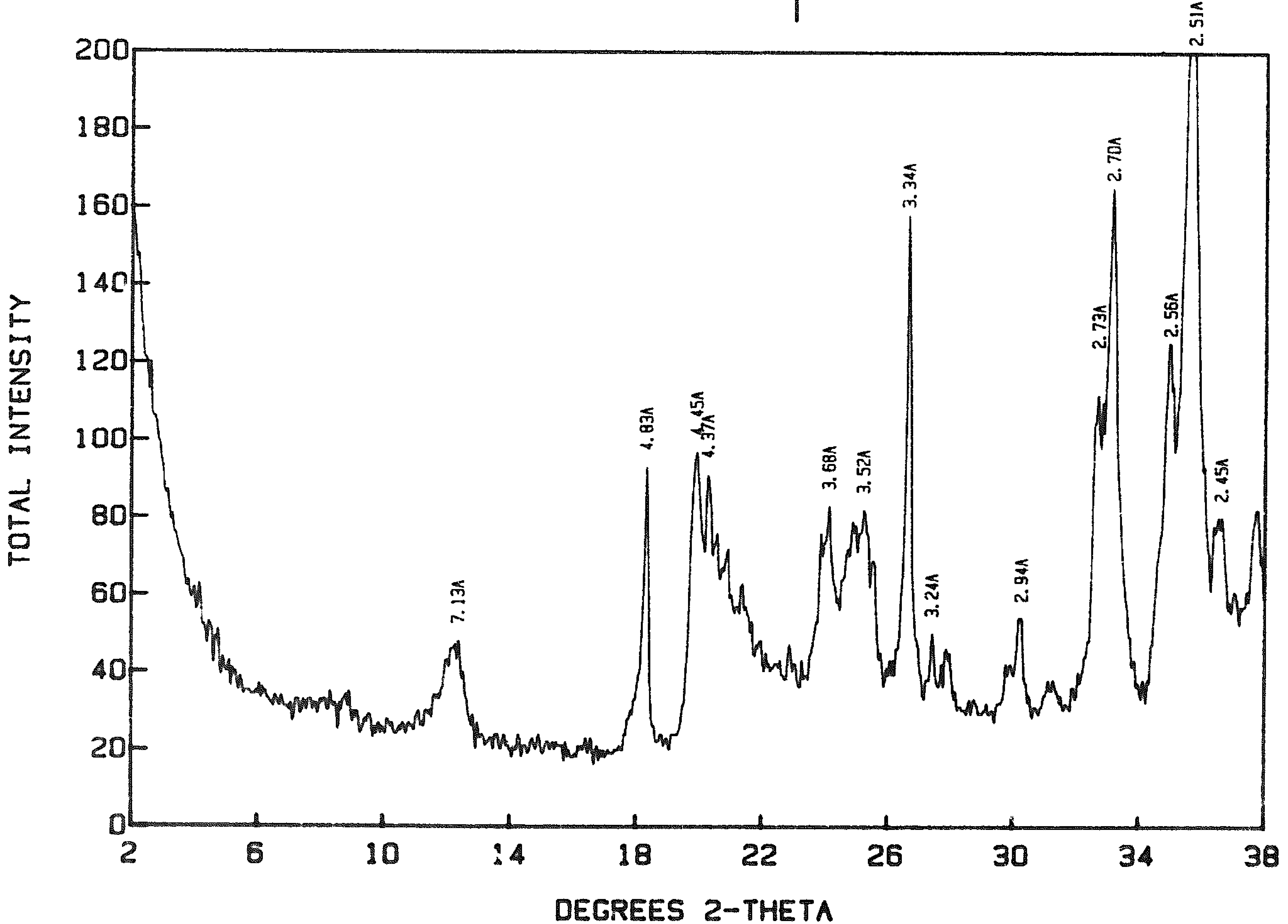
Volume Number 116; File Number D880630.2

SITE 5 3Bt



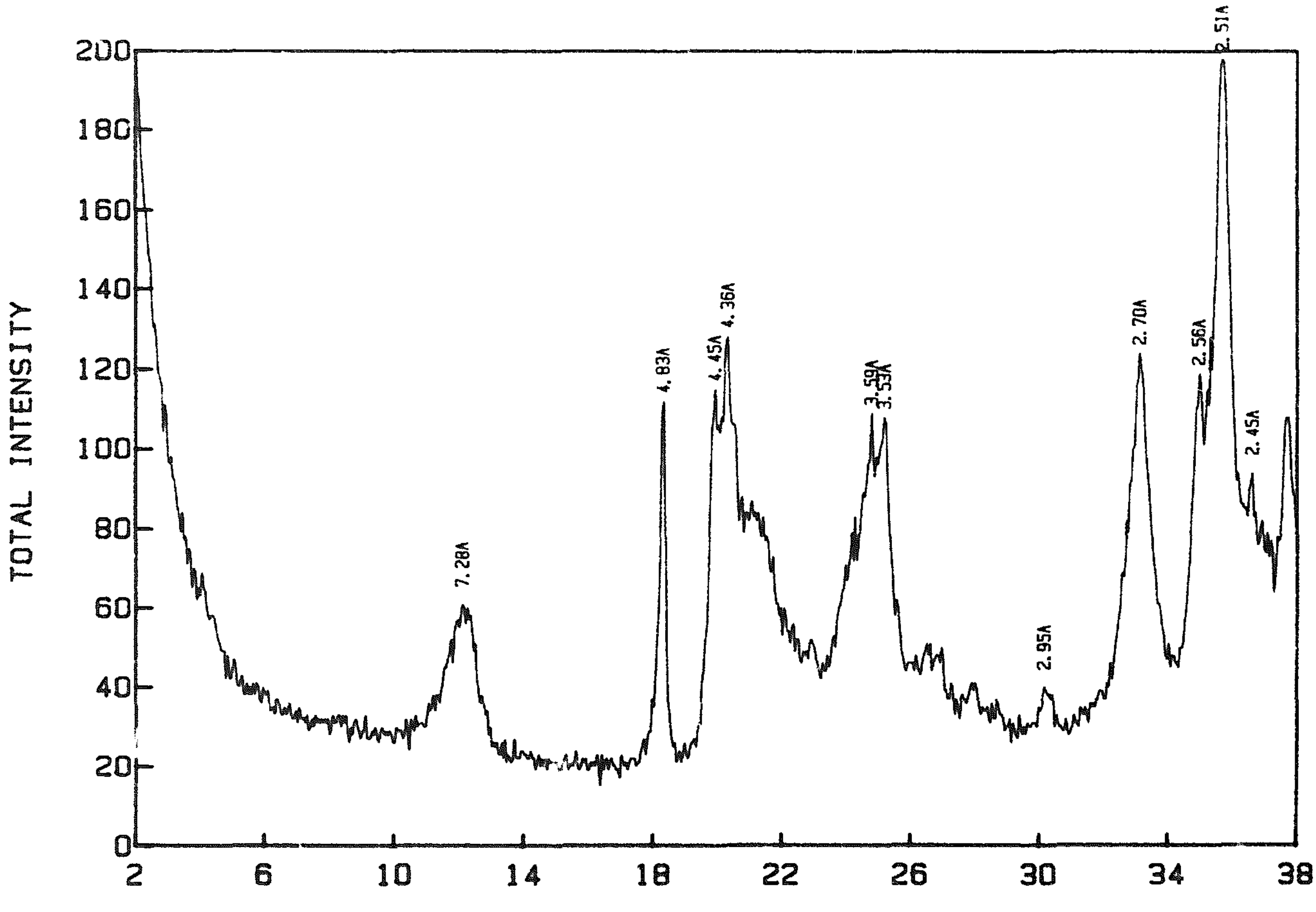
Volume Number 151; File Number D890123.1

SITE 6 Ap



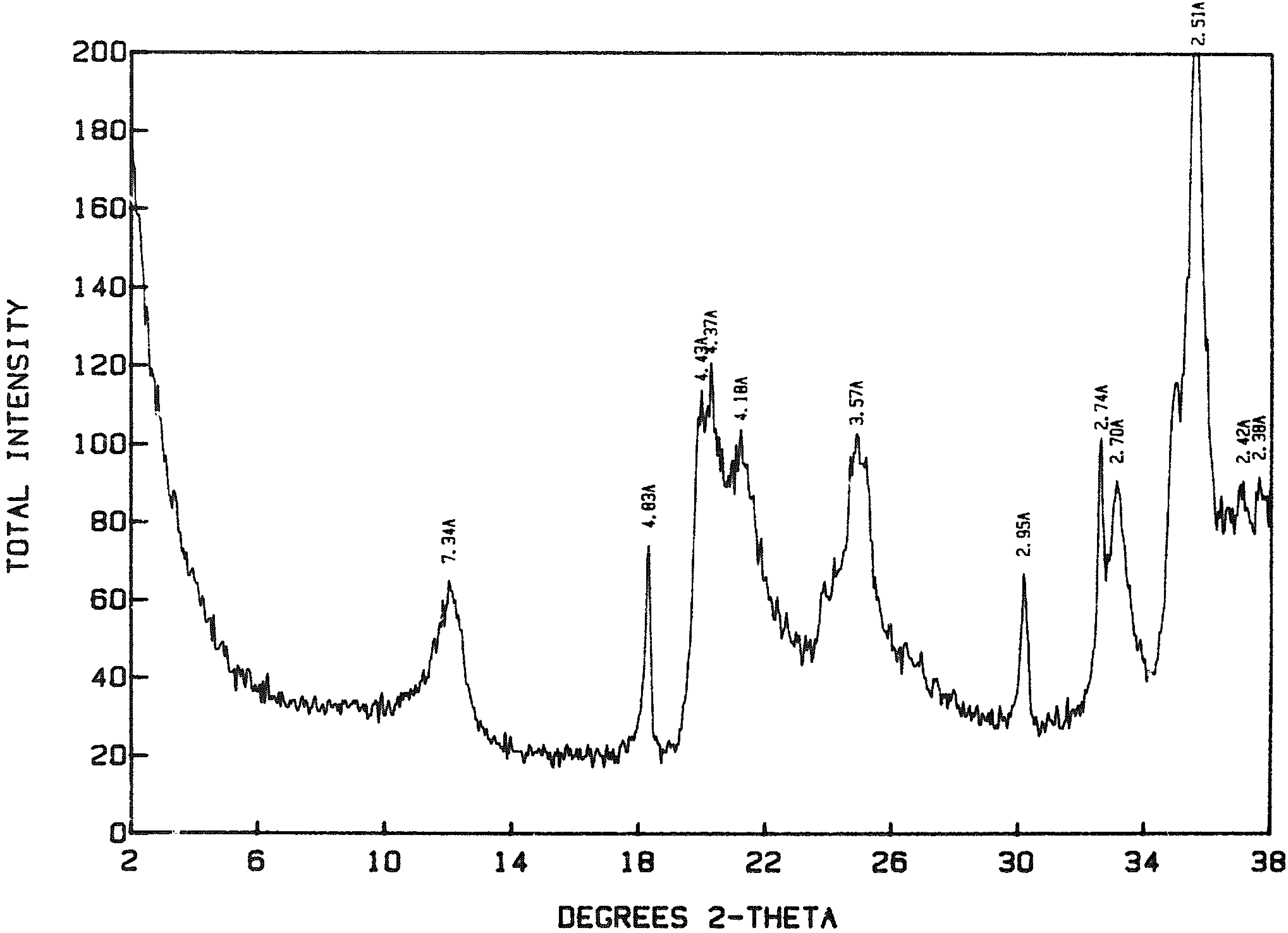
Volume Number 118; File Number D880714.4

SITE 6 Bw2



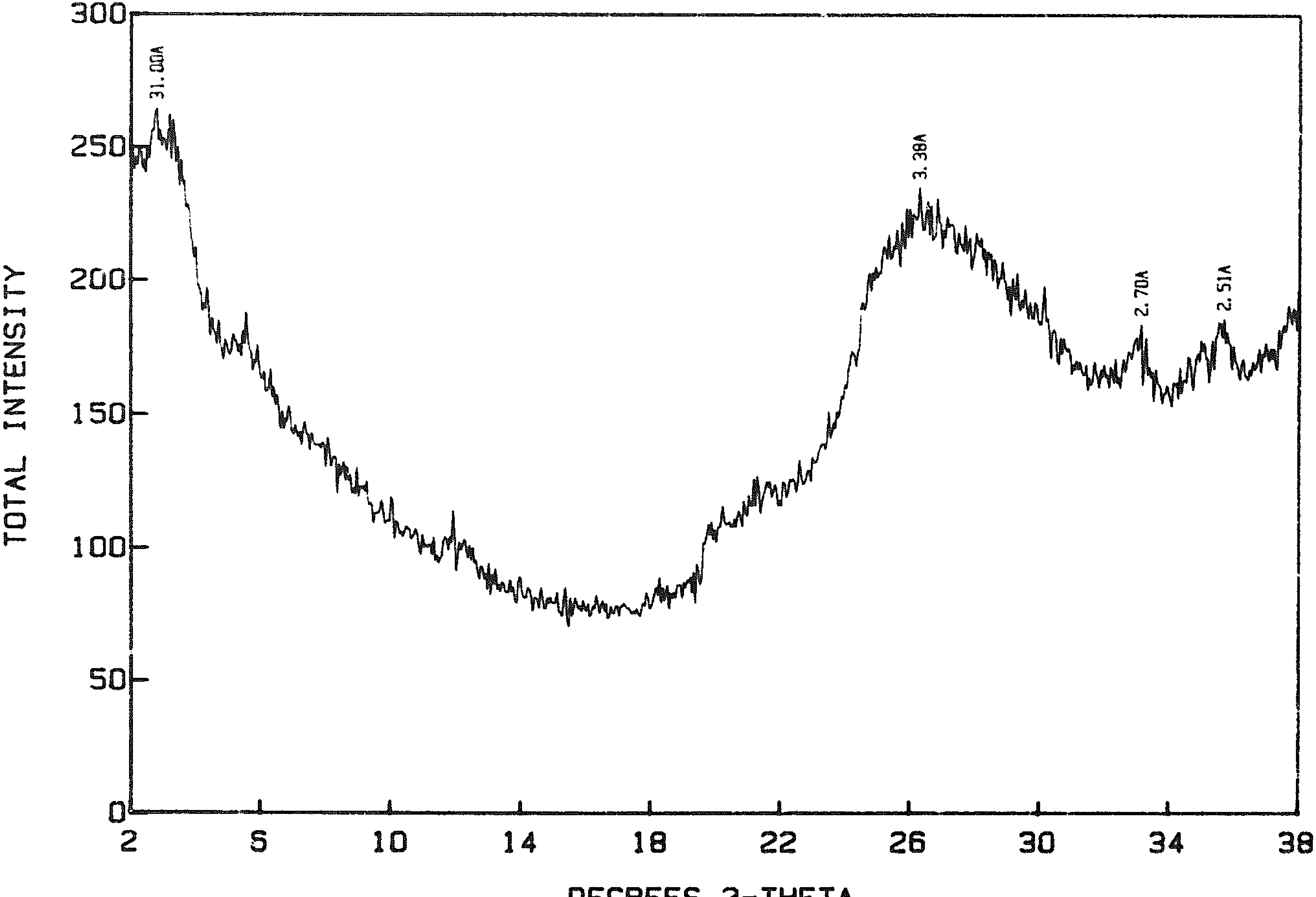
Volume Number 118; File Number D880714.1

SITE 6 2Bt



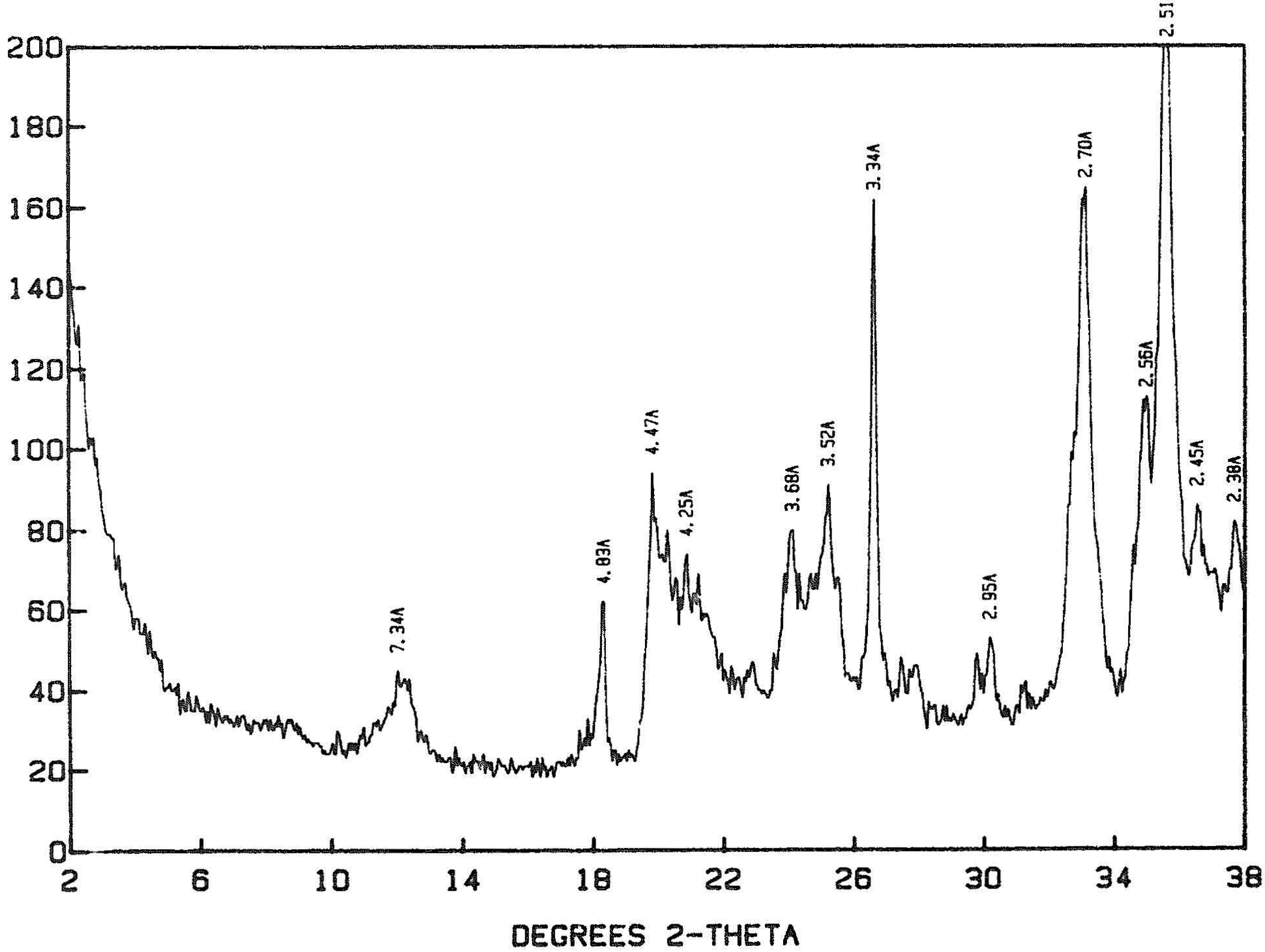
Volume Number 118; File Number D880714.2

SITE 6 ASH



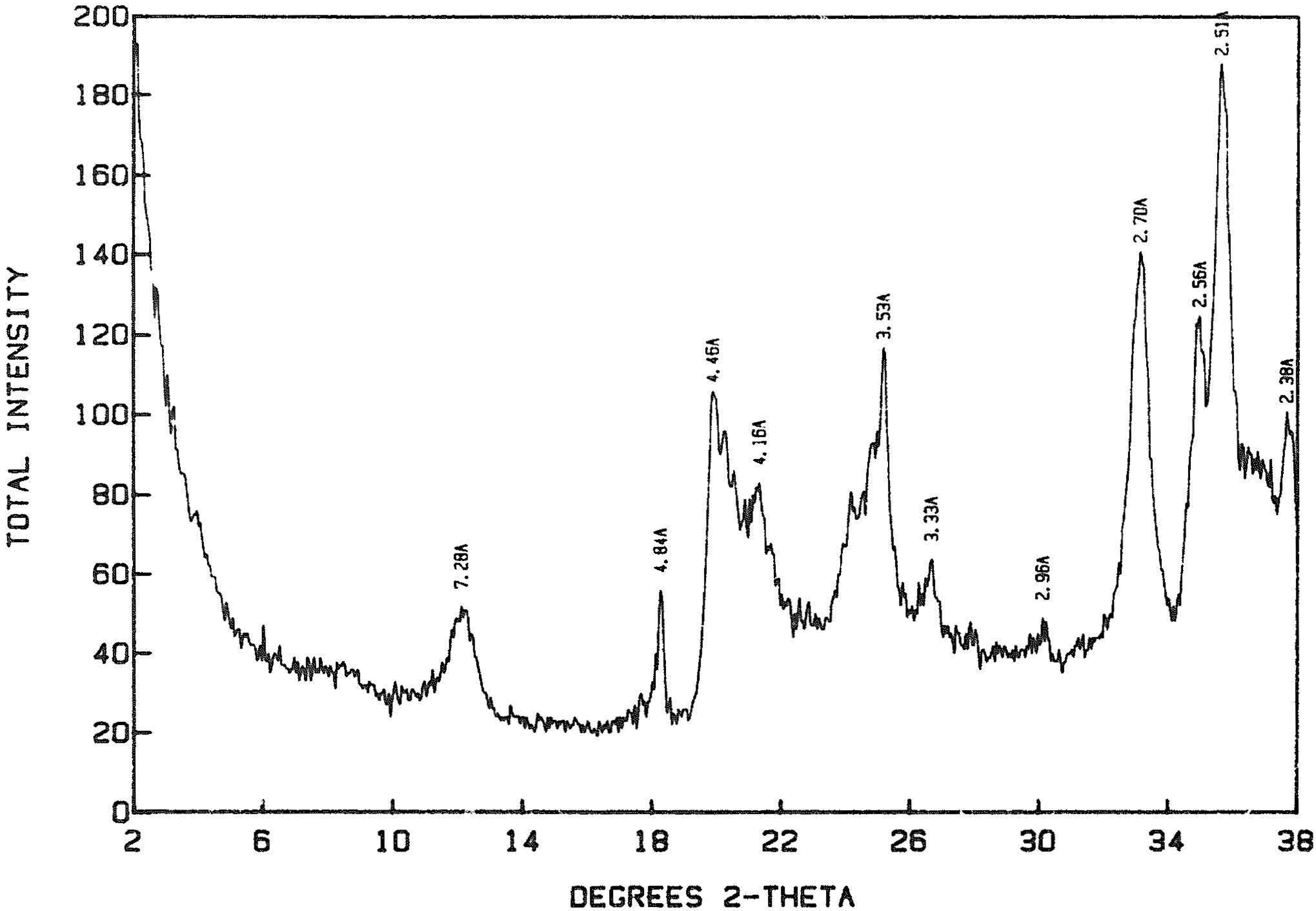
Volume Number 116: File Number D880629.2

SITE 7 A



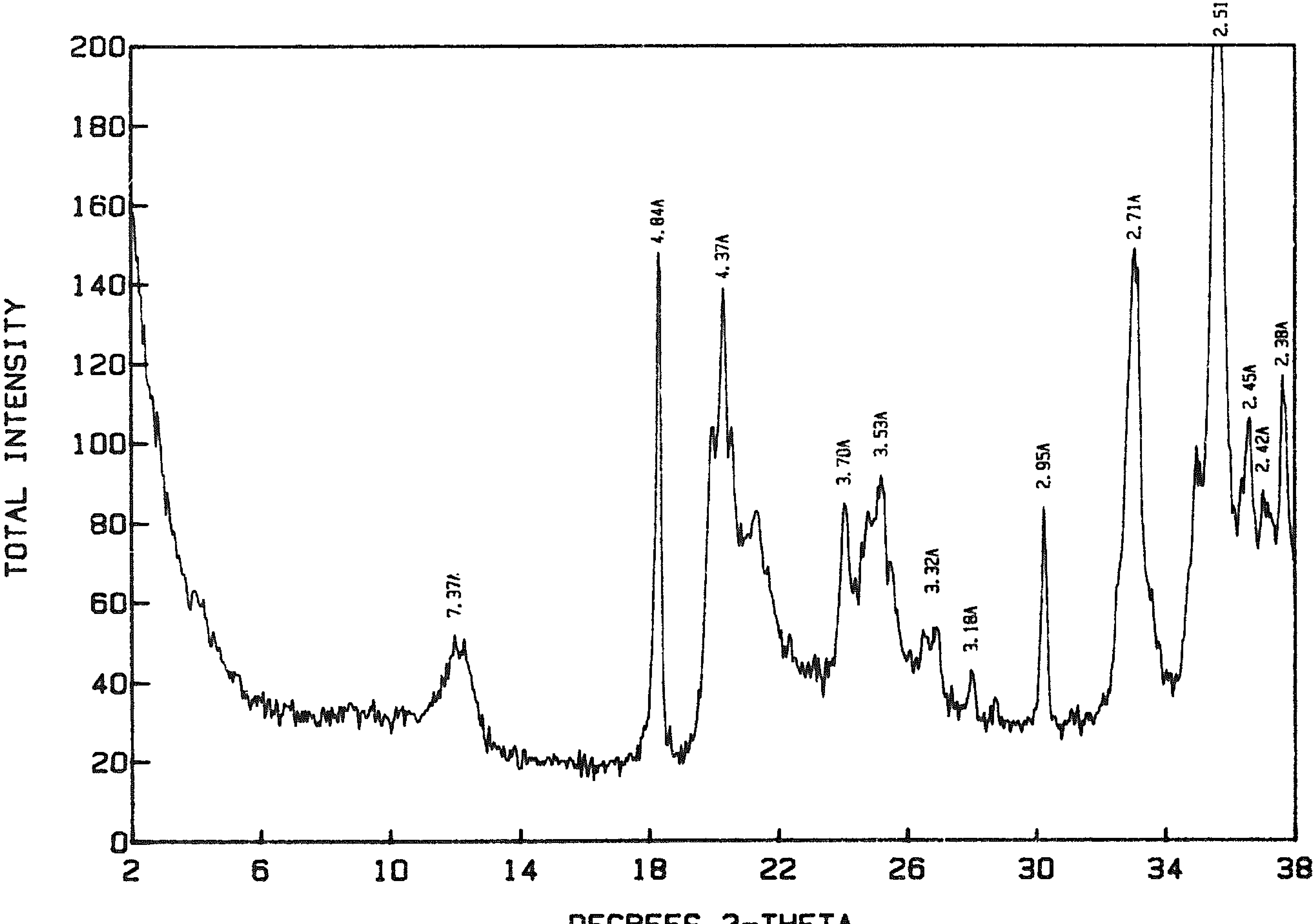
Volume Number 116; File Number D880629.1

SITE 7 Bw



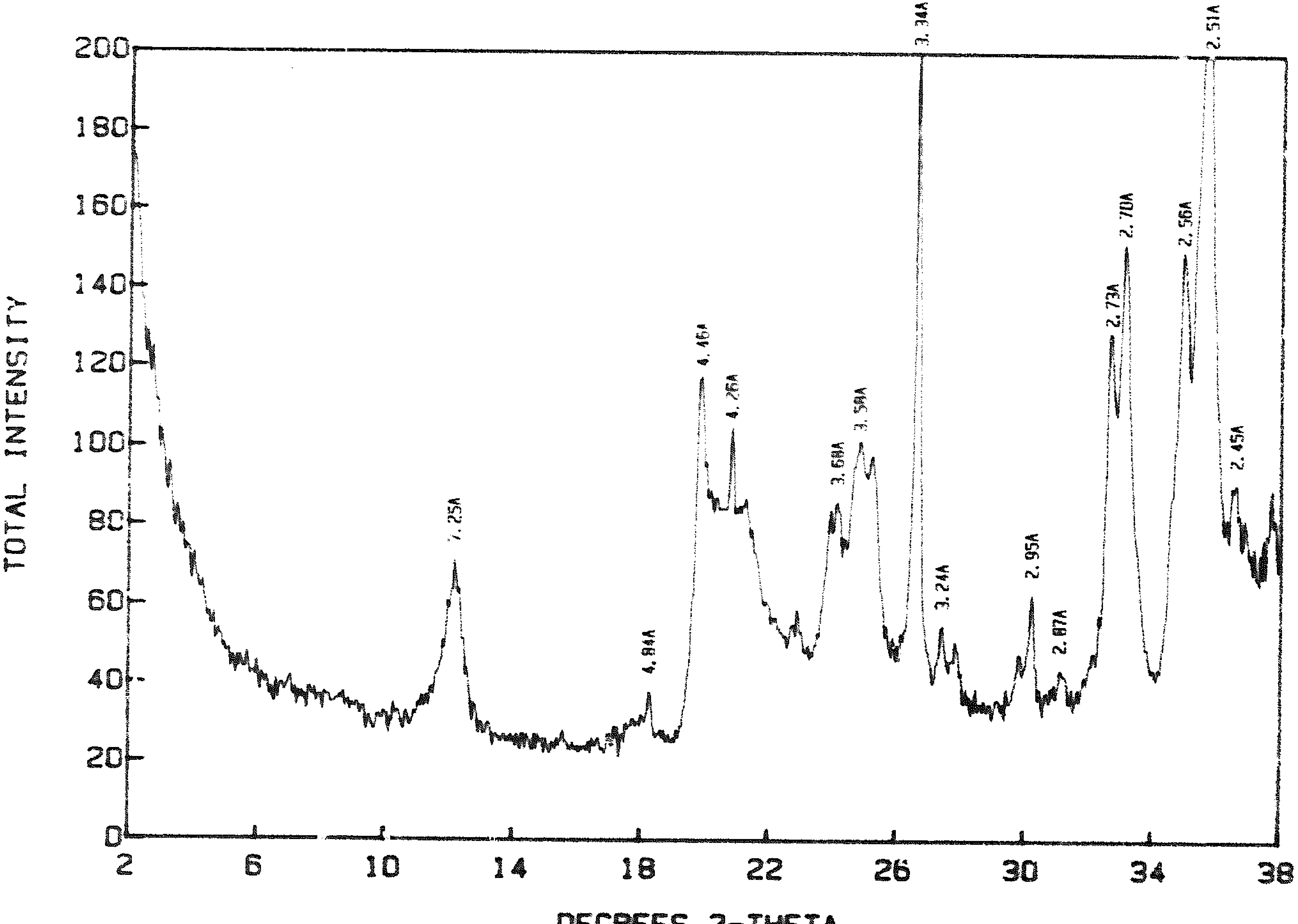
Volume Number 115; File Number D880628.4

SITE 7 2Bt



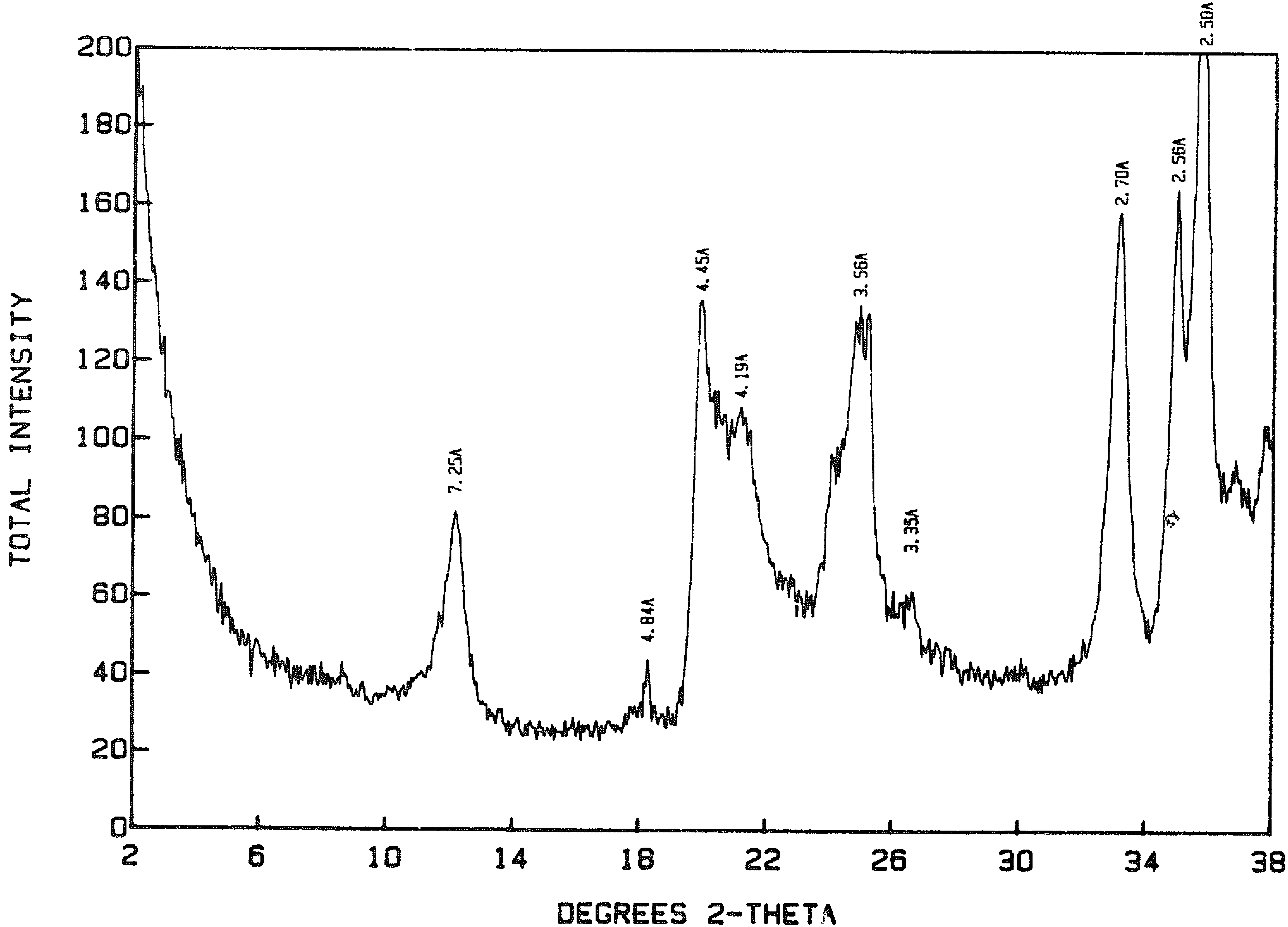
Volume Number 115; File Number D880628.5

SITE 8 A



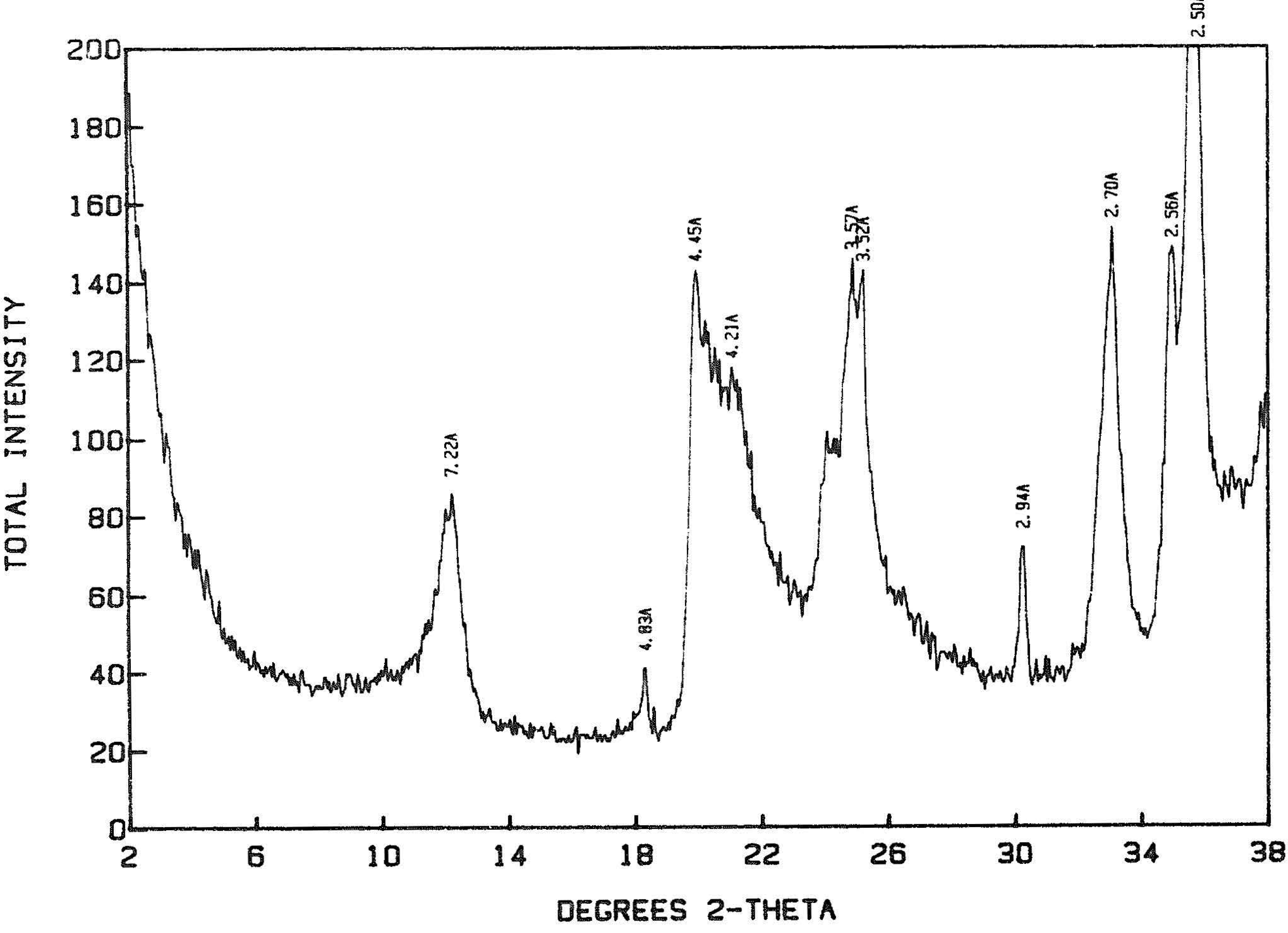
Volume Number 103; File Number D880512.4

SITE 8 2Bw



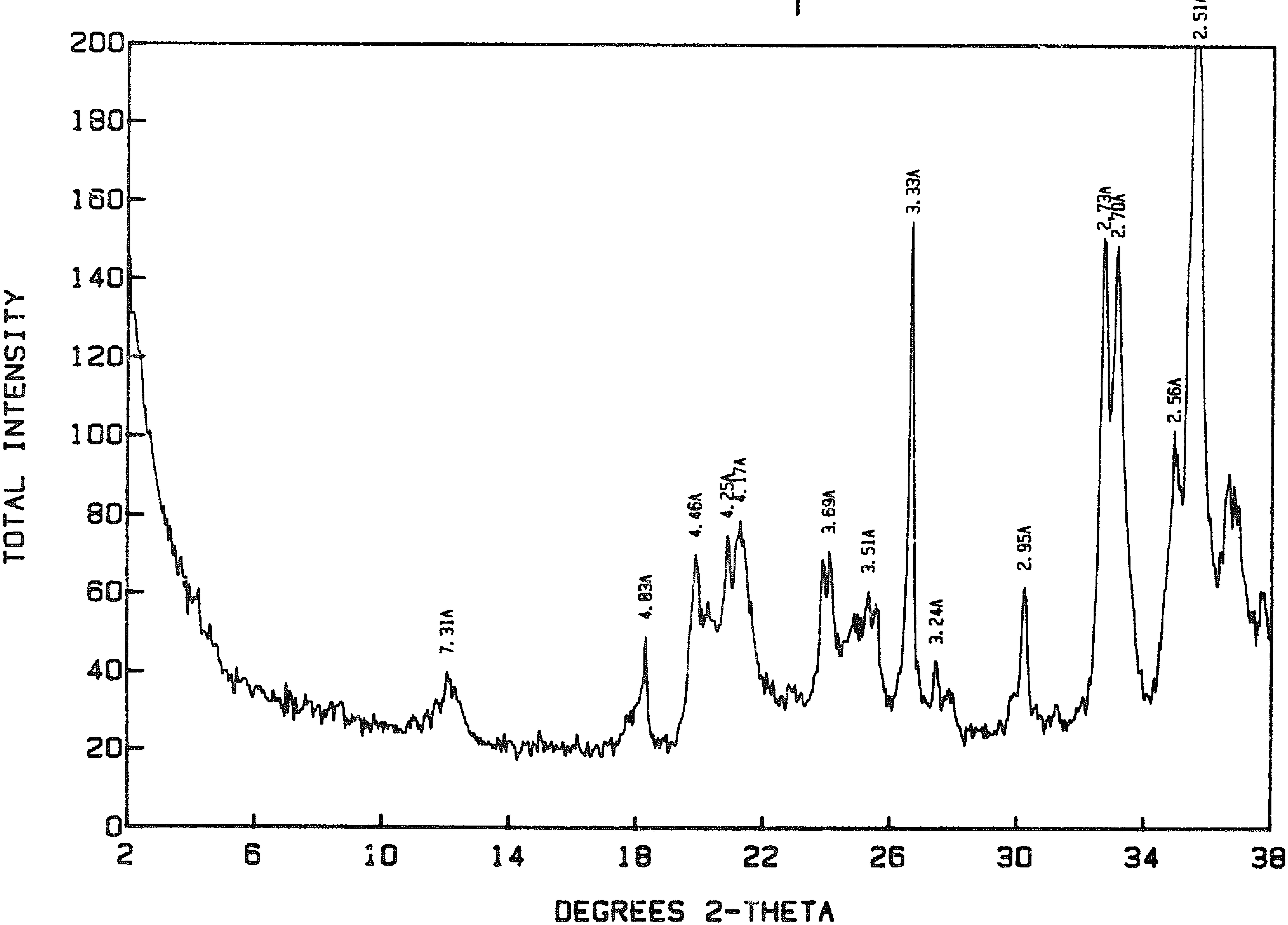
Volume Number 103; File Number D880511.1

SITE 8 3Bt



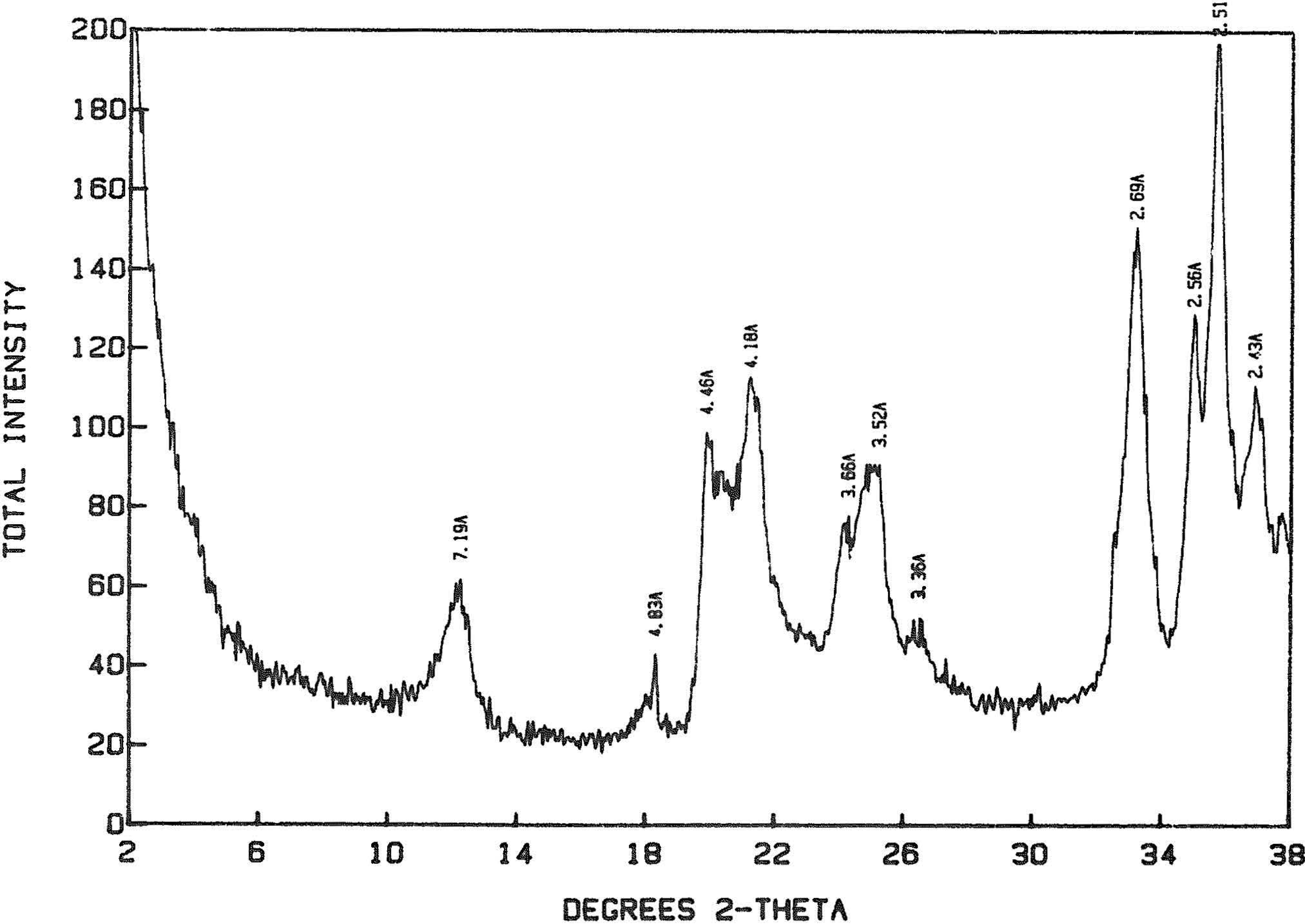
Volume Number 103; File Number D880511.2

SITE 9 Ap2



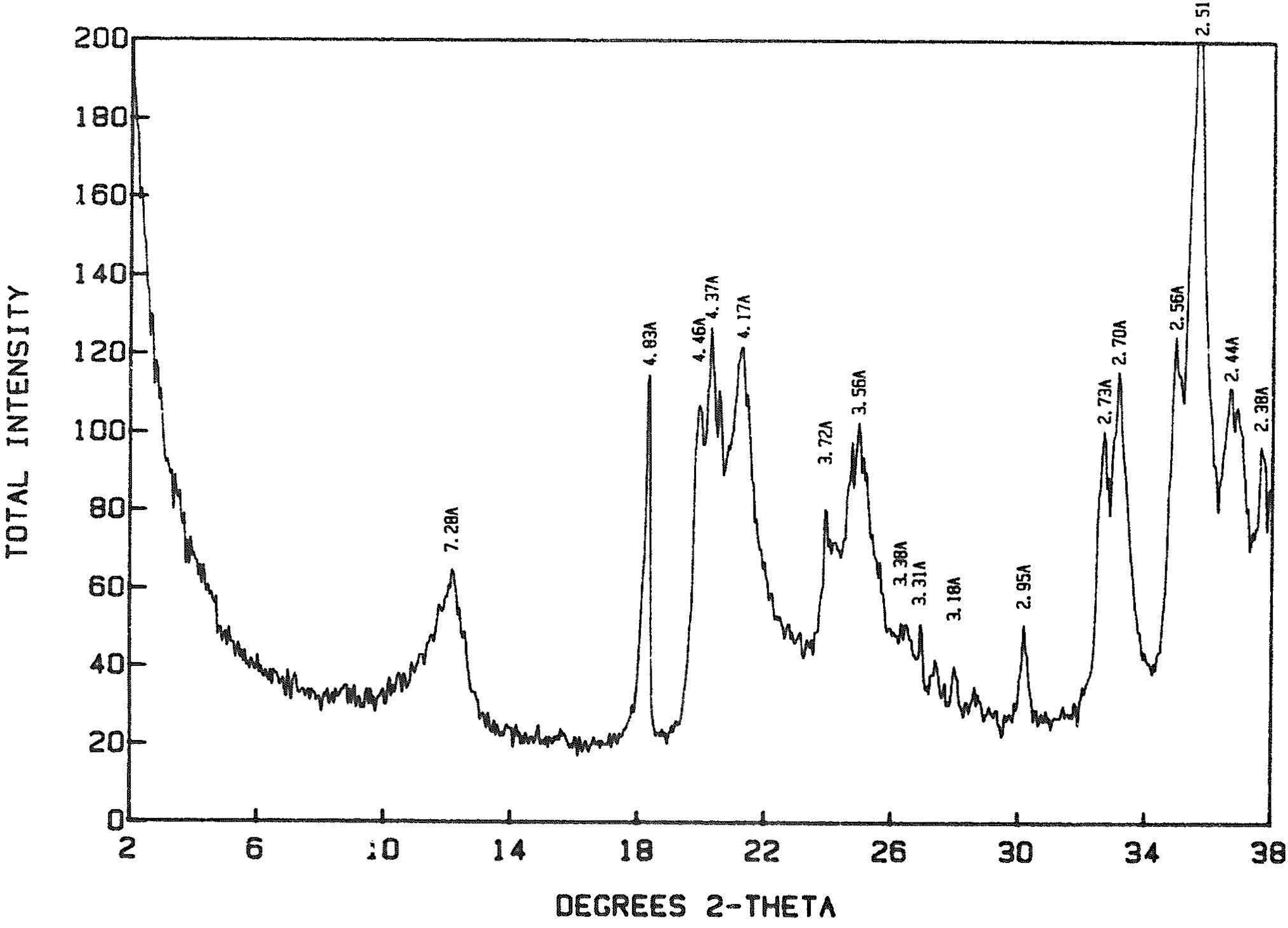
Volume Number 105; File Number D880517.3

SITE 9 2Bt2



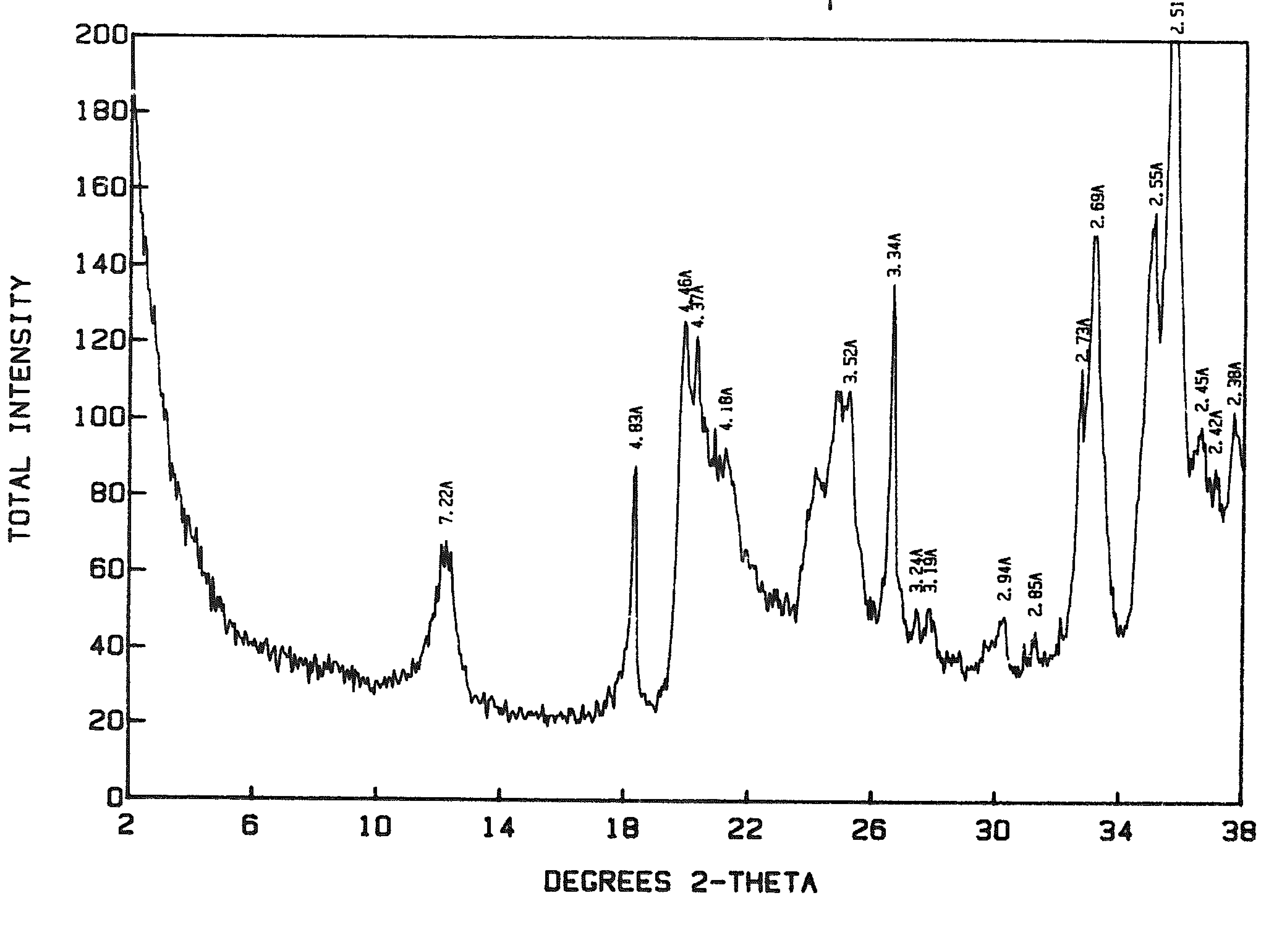
Volume Number 94; File Number D880420.4

SITE 9 3Bt4

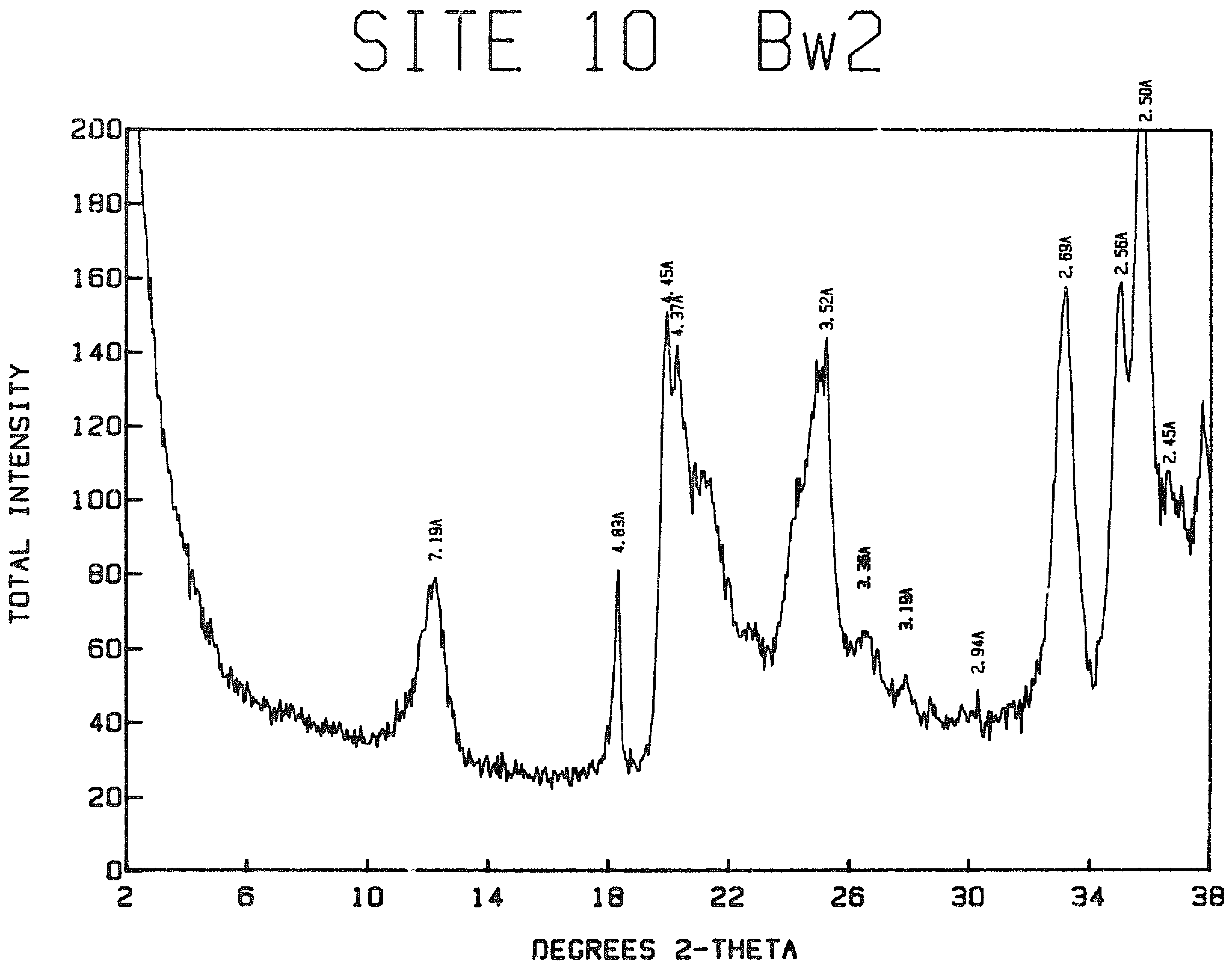


Volume Number 94; File Number 0880420.2

SITE 10 Ap

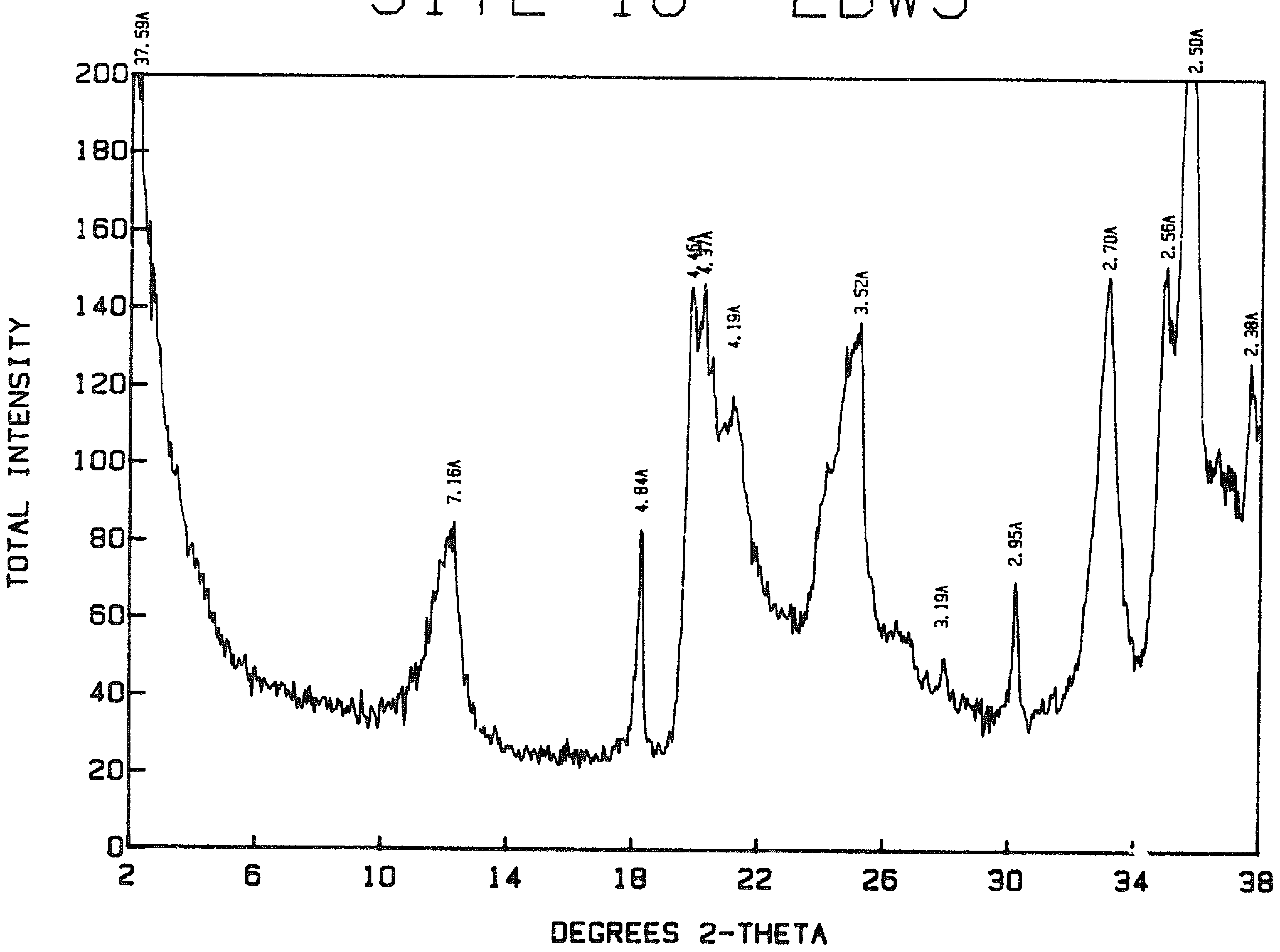


Volume Number 105; File Number D880518.5



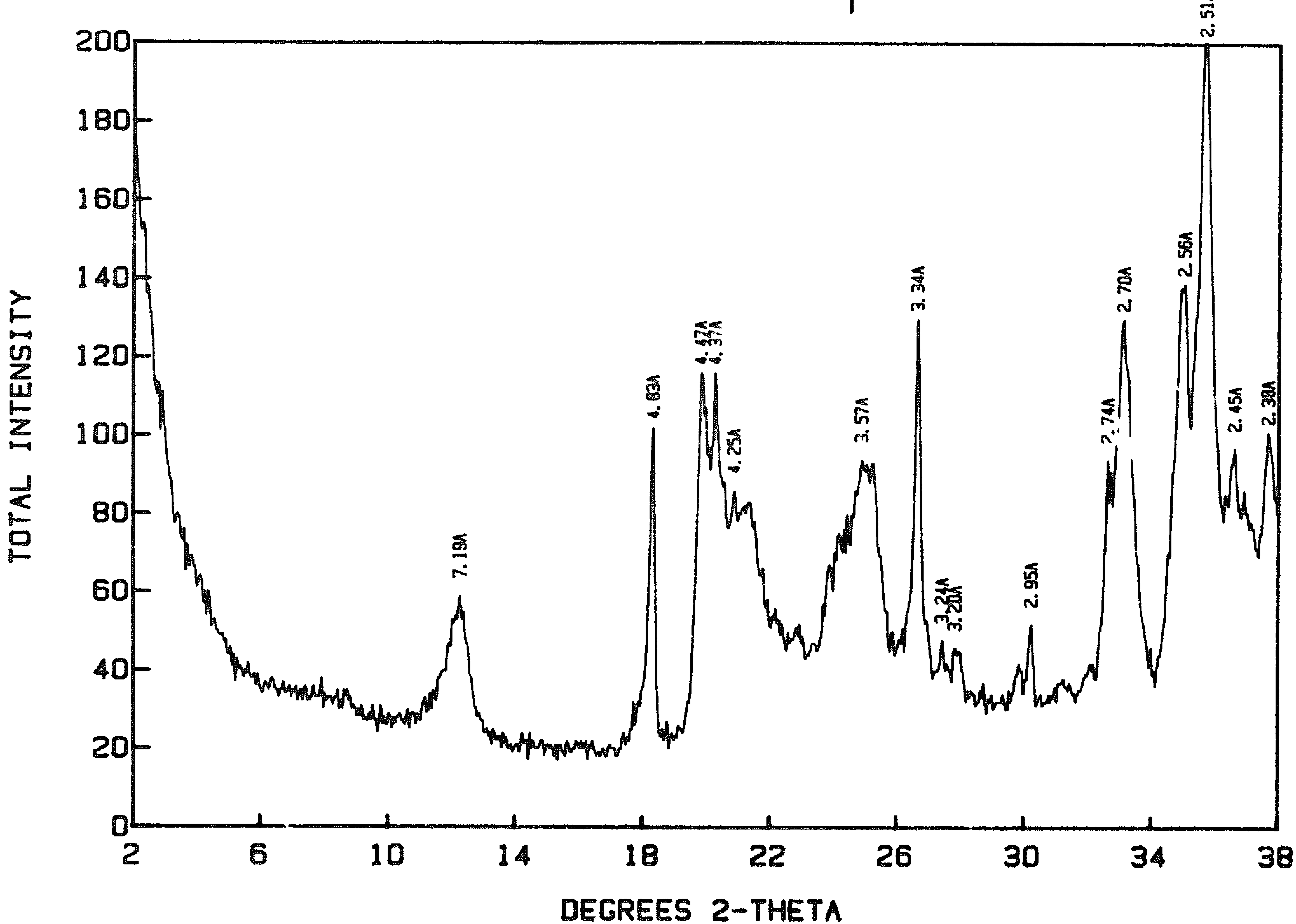
Volume Number 89; File Number D880407.1

SITE 10 2Bw3



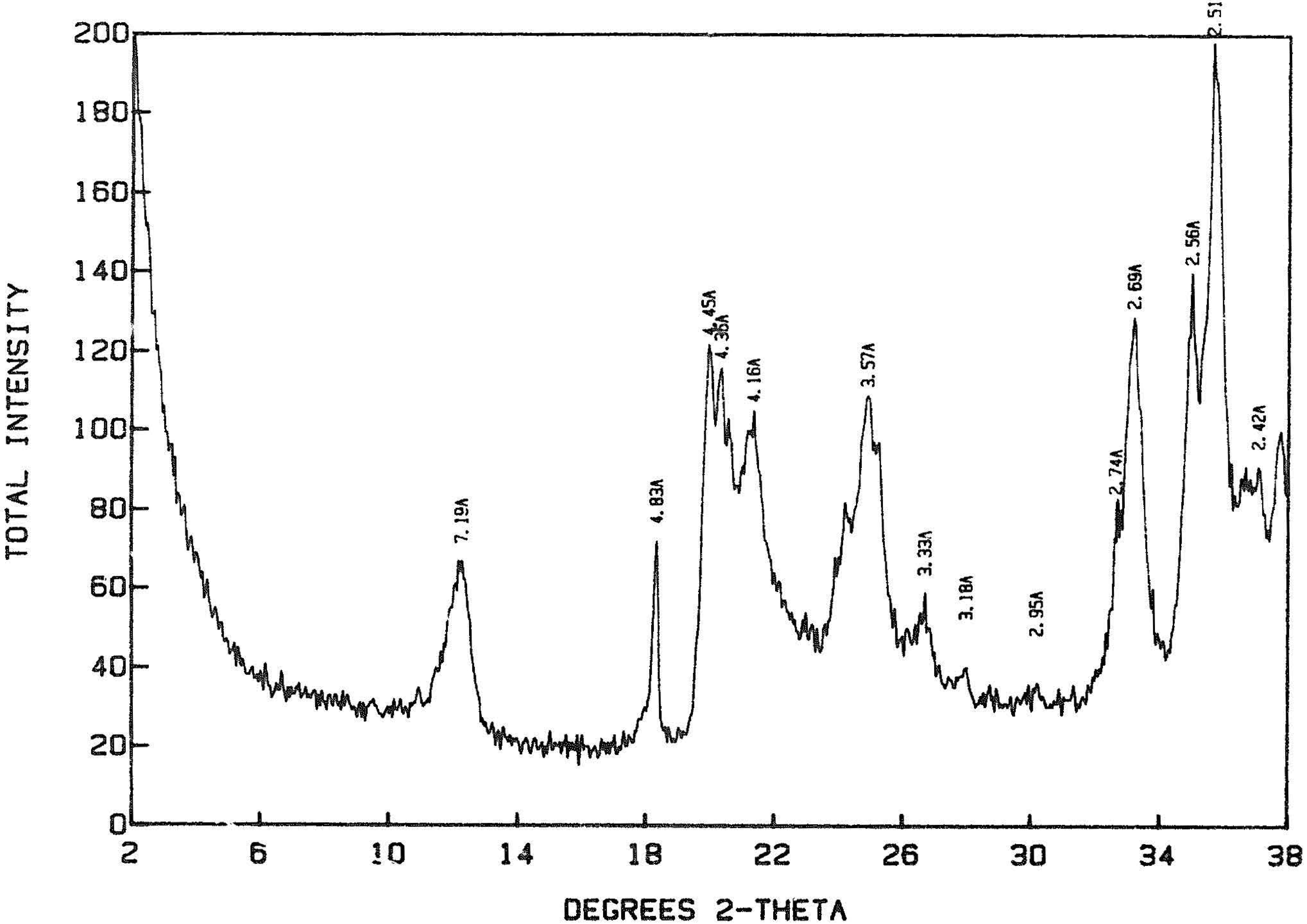
Volume Number 89; File Number D880407.3

SITE 11 Ap2



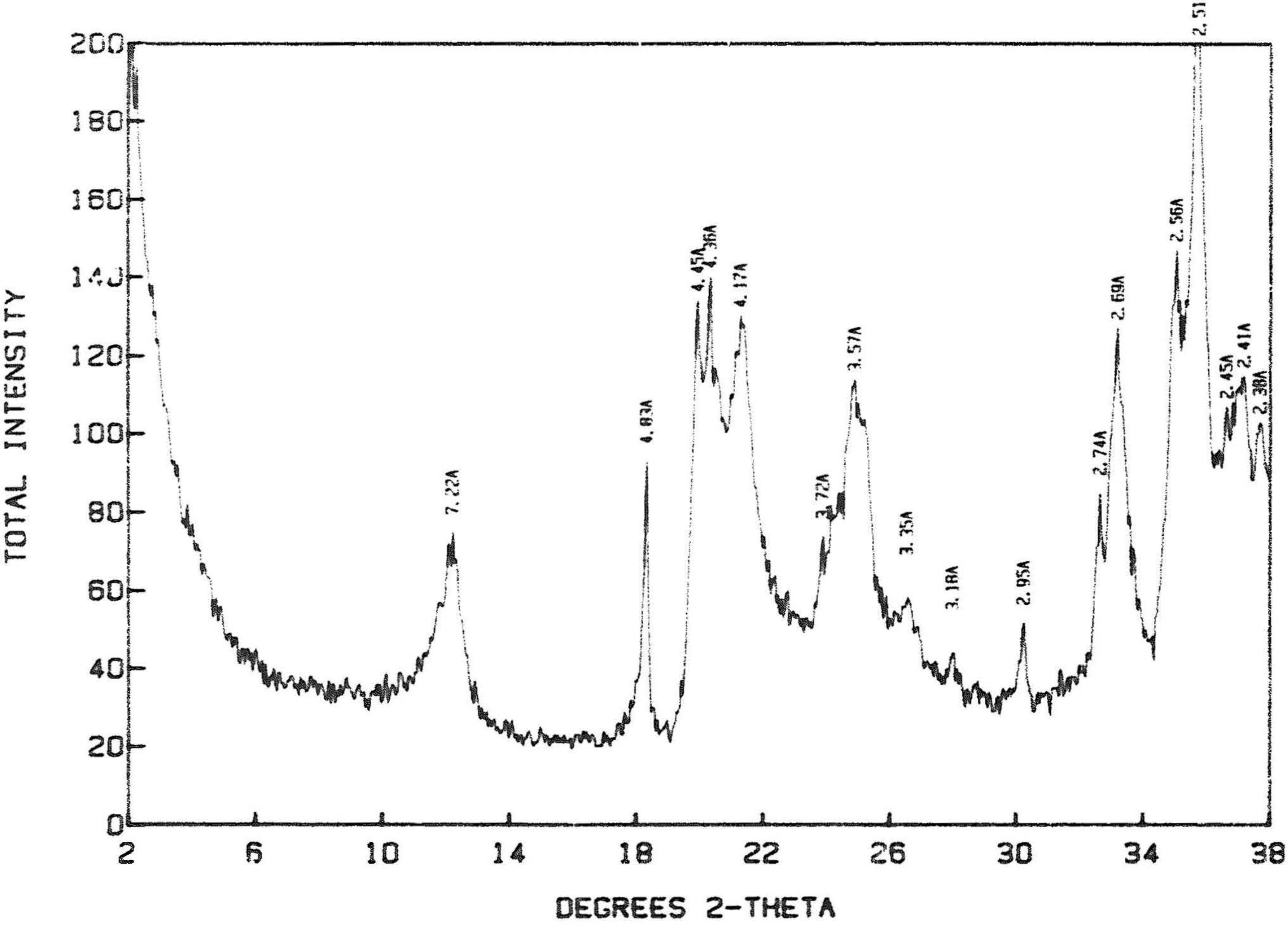
Volume Number 117; File Number D880704.2

SITE 11 Bw



Volume Number 117: File Number D880704.1

SITE 11 2Bt3



Volume Number 95; File Number 0880422.4